

Historic, Archive Document

Do not assume content reflects current scientific knowledge, policies, or practices.

eserve
TS195
2
L37
945

INFLUENCE OF TEMPERATURE ON RELATIVE HUMIDITY WITHIN CONFINED SPACES WITH AND WITHOUT A DESICCANT

November 1945

MAR 05 2011

BY:



No. R1498

**UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
FOREST PRODUCTS LABORATORY
Madison 5, Wisconsin
In Cooperation with the University of Wisconsin**

INFLUENCE OF TEMPERATURE ON RELATIVE HUMIDITY
WITHIN CONFINED SPACES WITH AND WITHOUT A DESICCANT

By LEON LASSEN, Engineer

Introduction

In an analysis and interpretation of all data available in regard to the influence of temperature changes on the relative humidity within a package that contains both a desiccant and dunnage, special attention was given to those properties of silica gel and wood that are instrumental in the determination of the relative humidity of a package. These properties are described and then applied in numerical examples, which are used to evaluate the characteristics of the desiccants. Information is given on the rate of adsorption of silica gel and the influences that determine these rates. Data are furnished on the relationship between outside shade temperatures and temperatures within containers, and an estimate is made of the probable maximum temperature within a container when exposed to sunlight. Computations are also made to show the influence of extreme high and low temperatures on the relative humidity within a container. The influence of thickness, relative humidity, and pressure on the permeability constant of permeable barriers is also discussed. In following the examples given in the text the reader should refer to table 1 or to a chart showing the moisture content of air at various temperatures.

In general it may be stated that sufficient data are presented in the analysis to answer almost all the questions that have been raised as to the influence of extreme changes in temperature on the relative humidity within a container.

In preview the report shows that:

- 1a. The relative humidity of a space within an impermeable or nearly impermeable barrier, without desiccant or dunnage, decreases with an increase and increases with a decrease of the temperature of the space within the barrier.
- b. The change in relative humidity is almost simultaneous in time with the temperature change within the barrier.
- c. Temperature and humidity conditions may occur which are favorable to condensation of the confined vapor.
- 2a. A desiccant within a space confined by a barrier will reduce the relative humidity within the space.

b. The magnitude of the reduction is determined by the amount of desiccant used.

c. The time required for the desiccant to establish equilibrium is dependent on the amount of desiccant, the size and shape of the package of gel and the temperature and relative humidity of the space within the package.

d. If the amount of gel used is in accordance with various specification formulas, safe conditions within a package are usually established in 2 to 3 hours at ordinary temperatures.

e. The rate at which silica gel picks up moisture increases with an increase of temperature, relative humidity, or both.

f. Once equilibrium is reached a desiccant will practically eliminate fluctuations in relative humidity that would occur in a container without a desiccant when subjected to temperature changes.

3a. The relative humidity conditions within an impermeable barrier, in which a desiccant is enclosed, can be predicted with a high degree of accuracy no matter how extreme the expected changes in temperature may be.

b. The relative humidity conditions within a permeable barrier cannot be predicted with any degree of assurance due to the fact that the permeability constant of the usual barrier material is affected by changes in temperature and may also be affected by changes in vapor pressure differential.

c. Methods for determining the permeability constant of the more or less permeable barrier material need further study to determine the influence of the type of vapor flow on the constant.

4a. A package to be exposed to an extreme change of outside temperature within a relatively short period of time may have an extreme lowering of temperature within as little as one-half hour. A considerably longer period of time, however, is required to obtain an equal lowering of temperature within the container.

b. An appreciable period of time for changes of temperature to occur within a package is a favorable phenomenon, since it allows time for the desiccant to act to maintain a low relative humidity, which tends to increase with a decrease in temperature.

c. Based on tests made at the Laboratory it is estimated that the temperature within a container will not exceed 165° F. (74° C.) under the exposure of the hottest shade temperature on record.

5. Dunnage¹ with a moisture content of 4 percent or less may be used as a desiccant in impermeable barriers. Dunnage cannot, however, be recommended

¹The word dunnage as used in this report is restricted to wood, fiberboard, and regenerated wood fiber.

as a desiccant within permeable barriers because of difficulties involved in replacing the dunnage. When used with a permeable barrier, the moisture content of dunnage should not exceed 3 percent.

Silica Gel

Silica gel is a prepared form of silicon dioxide having an extremely porous structure. It is made by mixing predetermined concentrations of an acid, such as sulfuric acid, and a soluble silicate (water glass), and allowing the mixture, known as hydrosol, to set to a jelly-like mass called hydrogel. At this stage of its manufacture it is in the form of a colloid. After setting, the hydrogel is broken into small lumps and thoroughly washed to remove excess acid and the salts resulting from the reaction. The washed hydrogel is then dried, crushed and screened to the desired particle size and given a final activation.

The final product is an inert rugged material with a hardness of about No. 5 in Mohr's Mineralogical Scale, or slightly softer than ordinary window glass. The action of silica gel in absorbing vapors is purely physical and there is no change in the size or shape of the particles as they become saturated. Even when saturated the particles of silica gel feel and appear perfectly dry.

In order to understand the action of silica gel in practical applications, the reasons for the particular action of the gel which makes it applicable to packaging work will be discussed.

Surface Area and Capillaries

It is known that almost every solid is capable of adsorbing gas or vapor on its surface to some degree, and that the weight of gas adsorbed depends upon the nature and extent of the surface. Silica gel commonly used for packaging work will adsorb 40 percent of its weight of water from saturated air. This is far in excess of the adsorption capacity of most solids and is due to the porous structure of the gel. The dimensions of its pores are less than the wave length of light and cannot be observed by known optical means. It has been estimated that 1 cubic inch of silica gel contains pores having a surface of about 50,000 square feet. With the enormous internal surface and infinite number of small capillaries, the gel attracts vapors, condenses them, and holds them as liquids in the pores or capillaries.

Factors Affecting Adsorption Capacity

The weight of vapor adsorbed on silica gel depends upon partial pressure of the vapor in the original gas mixture, the temperature of the silica gel and of the gas mixture, the surface tension of the condensed liquid, its ability to wet porous surfaces, and the volume and shape of the pores.

Pressure of the Original Gas Mixture.---Of particular importance is the fact that silica gel will absorb water vapor from a gas mixture until the pores of the gel are filled to a point where the internal vapor pressure of the adsorbed liquid in the pores at a given temperature approaches as a limit the partial pressure of the vapor in the surrounding atmosphere at the same temperature. The adsorption of water vapor by a particular form of gel as influenced by temperature and vapor pressure is shown by the family of curves in figure 1, which is copied from a paper by Frank C. Dehler (4). Each curve of the family shows the amount of water adsorbed by gel when it is in equilibrium with water vapor pressure at saturation and how the amount adsorbed decreases with an increase of temperature. For purpose of analysis consider the curve marked 0.25 inch Hg - 41° F. (5° C.). This indicates that the silica gel is saturated with water vapor when the vapor pressure is 0.25 inch of mercury. Note that at this temperature the gel has adsorbed water equal to 40 percent of its weight on the dry basis. This is the maximum amount of water that this particular gel will adsorb at this temperature.

Temperature.---Consider that the temperature of the air and silica gel is 60° F. (16° C.) instead of 41° F. (5° C.), as assumed in the preceding paragraph, but that the same total amount of vapor that caused saturation at 41° F. (5° C.) is still present. The curve marked 0.25 inch Hg - 41° F. (5° C.) shows that at 60° F. (16° C.) the adsorptive capacity of gel for vapor is reduced to 30 percent of its dry weight. It is interesting to note that the relative humidity has been reduced from 100 percent (saturation) at 41° F. (5° C.) to 44 percent at 60° F. (16° C.) by the assumption that the absolute amount of vapor remained the same for the two temperatures. This arises from the fact that the saturation vapor pressure at 60° F. (16° C.) is 0.52 inch of mercury while the actual pressure is only 44 percent of the value or 0.25 inch of mercury.

For purposes of further clarification of the influence of temperature, assume that the vapor pressure remains 0.25 inch of mercury, but that the temperature is 100° F. (38° C.). The 0.25 inch Hg - 41° F. (5° C.) curve shows that at this temperature the gel will now adsorb only 12 percent of its own dry weight in water. At 100° F. (38° C.) the saturated water vapor pressure is 1.93 inches of mercury, and if the pressure is only 0.25 inch of mercury the relative pressure or humidity is 13 percent.

Relative Humidity.---The curve marked 2 inches Hg - 101° F. (38° C.) (fig. 1) indicates that the saturated vapor pressure for a temperature of 101° F. (38° C.) is 2 inches of mercury. The curve shows that for 100 percent relative humidity the gel will reach equilibrium when it has adsorbed water vapor equal to 40 percent of its weight when dry. Note that the 0.25 inch Hg - 41° F. (5° C.) curve also showed that the gel was capable of adsorbing 40 percent of its dry weight in water when the relative humidity under this condition was 100 percent.

In the second portion of the first problem it was shown that under a vapor pressure of 0.25 inch of mercury, a temperature of 60° F. (16° C.), and a relative pressure of 44 percent the capacity of the gel was 30 percent. To determine, for example, if a relative humidity of 44 percent from a saturation pressure of 2 inches of mercury will also establish the capacity

of the gel to be 30 percent, divide the 2 inches by 0.44 to get the saturation pressure of 4.54 inches which is shown by standard vapor pressure tables to occur at a temperature of 130° F. (54° C.). Using the 2 inch Hg - 101° F. (38° C.) curve it may be seen that the 30 percent water vapor adsorptive capacity corresponds to a temperature of 130° F. (54° C.) on the curve. The fact is therefore established that the adsorptive capacity of gel is dependent entirely on the relative humidity or relative pressure and that it is dependent on temperature only insofar as the temperature influences the relative humidity. It is possible therefore to develop a curve relating the percentage of water adsorbed by silica gel with the percentage of relative humidity as shown in figure 2. The application of the curve will be discussed in full later in the text.

Application

In packaging work silica gel is used for the partial drying of the air in enclosed spaces within a container. The air is dried to a degree that experience indicates will prevent damage by corrosion to metal products and mildew and mold to the container. In this application it is necessary that the packaged part and the gel be enclosed in a moisture barrier that either limits the entrance of moisture into the enclosed space to a predetermined maximum rate or prevents entirely the entrance of moisture into the space. The first type is usually a flexible barrier with moisture vapor transmission characteristics low enough to prevent the passage of moisture in excess of 0.25 gram per 100 square inches per day when subjected to a vapor pressure difference of 2 inches of mercury. The second type is a metal container in which the moisture infiltration rate is considered zero.

Amount Required

It is generally accepted that the corrosion of steel occurs when the relative humidity of the surrounding atmosphere exceeds 30 percent. In order to provide a factor of safety, however, sufficient silica gel is generally used in a package to maintain the relative humidity at some figure below 30 percent, and general agreement based on experience indicates the desirability of maintaining a relative humidity in a package not in excess of 20 percent.

Rate of Adsorption by Silica Gel

Tests and Results

For the purpose of packaging work silica gel is generally packed in small flat muslin bags containing from 2 ounces to 1 pound of silica gel.

Studies conducted at the Laboratory show that the rate of moisture pickup is considerably influenced by the size of the silica gel package, by the temperature, and by the relative humidity or relative vapor pressure of the surrounding air. The effect of these influences may be noted in table 2 and

in figures 3 through 8. The table and curves show that when a 1-ounce muslin bag of silica gel is placed in a No. 2-1/2 metal can with an open top and exposed to a controlled temperature of 130° F. (54° C.) and a relative humidity of 60 percent (vapor pressure 2.71 inch Hg) that it will reach equilibrium in 24 hours. A bag of gel of equal size similarly placed but exposed to a controlled relative humidity of 65 percent and a temperature of 80° F. (27° C.) (vapor pressure 0.66 inch Hg) will require 80 hours to reach equilibrium. With but few exceptions (due probably to experimental errors) the time required for silica gel in muslin bags to reach equilibrium increases with a decrease in relative humidity and in the temperature of the adsorbed liquid in its vapor stage.

When a 2-ounce bag of gel is emptied into a No. 2-1/2 metal can with an open top and exposed to a temperature of 130° F. (54° C.) and a relative humidity of 60 percent, the time required for the gel to reach equilibrium is only 12 hours (table 2) which should be compared to the 30 hours required for 2 ounces of bagged gel to reach equilibrium under the same exposure. A similar comparison of 4 ounces of bagged gel and 4 ounces of loose gel exposed to a temperature of 130° F. (54° C.) and a relative humidity of 60 percent shows that the bagged gel requires 50 hours and loose gel only 35 hours to complete the adsorption process. Similar comparisons of the loose and bagged gel exposed to other conditions show the same trend, which is that the gel in a loose condition reaches equilibrium quicker than the bagged gel.

Table 2 may also be used for the comparison of the effect of the size of the bag on the time required for gel to reach equilibrium. It may be noted, for example, that the time required for the bagged gel to reach equilibrium when exposed to a temperature of 130° F. (54° C.) and a relative humidity of 60 percent increases from 24 hours for the 1-ounce bag to 95 hours for the 8-ounce bag. The unbagged gel under the same vapor pressure condition increases from 12 hours for the 2-ounce bag to 35 hours for the 4-ounce bag. Comparisons of the other exposure conditions indicate that it is characteristic for the larger quantities of gel to require longer periods of time to attain equilibrium when exposed to the same temperature and humidity conditions.

Before proceeding with deductions as to the influence of the previously discussed characteristic on the application of gel to packaging work it would be well to discuss this property from another viewpoint. Table 3 lists the time in hours required for packages of various sizes filled with silica gel to adsorb 10 percent of its weight when exposed to constant conditions. Column 2 of table 3 shows that a 1-ounce bag placed in a No. 2-1/2 open top metal container adsorbed 10 percent water vapor in 2-1/2 hours when exposed to a vapor pressure of 2.71 inches of mercury. The 2-ounce bag under the same exposure conditions required 3 hours; and the 8-ounce bag, 7 hours. The other columns show similar results differing only in an increasing time requirement as the temperature and relative humidity decreased.

Table 4, which lists the percentage of moisture adsorbed at the end of a 5-hour period of exposure, gives still another indication of the same

characteristic. The data in this table indicate that the smaller bags adsorbed moisture at a faster rate than the larger bags and that the loose gel picks it up faster than gel of equal weight when bagged. Details of the relationship between moisture adsorption and time are shown in figures 3 through 8.

Layer Action

The explanation for the observations that smaller bags will adsorb moisture at a more rapid rate per unit of weight than larger bags and that the loose gel will adsorb moisture at an even greater rate lies in the fact that the smaller bags have a comparatively larger surface exposure per unit of weight than the larger bags and that the loose gel has a still greater surface exposure. In the action of adsorption, the surface layer of gel will adsorb moisture first, the adsorptive rate for each inner layer being determined by the area of interface contact between the next outer and inner layer.

The layer action of gel is clearly illustrated by gel impregnated with cobalt chloride solution (indicators). When freshly activated or when in equilibrium with the relative humidity of less than 10 percent this gel is deep blue in color. As it gradually adsorbs water, the outer layer changes color becoming pink, but the background of blue, which is still the color of the inner layers, gives the gel the appearance of being at some color between pink and blue. For example, at 30 percent relative humidity it has a distinct lavender color. This color fades to a pale pink at about 50 percent relative humidity and becomes decidedly pink as the relative humidity approaches 100 percent.

Influence of Adsorption Rate in Packages

General

In considering what use can be made of the adsorption-rate characteristics of silica gel in packaging work, it must be recognized that the experiment conditions used at the Laboratory to determine the characteristics may or may not be repeated in actual practice. In the tests with gel in open-top cans one end of a bag rested on the bottom while a side of the bag rested on a side of the can. In an actual package a bag may be tied with one side to a support thus limiting the exposed area to one side or it may be suspended giving full exposure. Thus absolute values listed in the table may not be reproduced, but it is believed that the indications and tendencies revealed by the study will hold true.

Determination of Amount of Gel Required Under Various Conditions

Example 1.--If the gel is used to prevent the occurrence of corrosion, the question arises as to how long a package can be subjected to a corrosive humidity condition before corrosion begins. Further study would be

required before this question could be answered. It is apparent, however, that any desired rate of adsorption can be obtained by the use of the proper combination of bag sizes. For example, assume a unit metal can is to be used as a barrier and that this can has a volume of 10 cubic feet. Assume further that there is a requirement that sufficient gel be placed in the container, which is to be without dunnage, to reduce the saturated condition at 130° F. (54° C.) to 20 percent relative humidity. The moisture content of air saturated at 130° F. (54° C.) is 0.00635 pounds per cubic foot and for 10 cubic feet would be 0.0635 pounds. Under an approximate rule, the gel (used for the data for fig. 2) showing a 20 percent relative humidity would contain 10 percent of its weight in water (fig. 2). The amount of gel required to reduce the relative humidity to 20 percent in this container would be $\frac{0.0635}{0.10} (100-20) = 0.508$ pound (8 ounces).

In actual practice it is unlikely that packaging will be done in a saturated atmosphere and in as high a temperature as 130° F. (54° C.). It will be more practical to assume a temperature of 80° F. and a relative humidity of 80 percent. There will be 0.00095 pound of moisture per cubic foot, or a total of 0.0095 pound (0.152 ounce) in the 10 cubic feet of the container when it is freshly sealed. It has been assumed, however, the sufficient gel has been put into the container to adsorb 0.8 x 0.0635 pound (0.80 ounce) of water vapor. The percentage adsorbed will therefore be reduced to approximately 2 percent and the relative humidity within the container to about 5 percent. Assume now that it is desired to use a single 8-ounce bag of gel. According to figure 6 the 8-ounce bag will adsorb 5 percent of its weight in moisture in about 4 hours, and from this it is evident that it will adsorb sufficient moisture from the container to reduce its relative humidity to 30 percent in less time than that.

If eight 1-ounce bags are used, the 2 percent moisture content will be reached in less than 2 hours.

Example 2 -- Using ANP-13-A Specification Formula.--In order to be assured that the previous problem presented the proper approach to an evaluation of the action of gel in a package with respect to time, consideration is given to the gel requirements of Specification ANP-13-A,² which requires that for moisture-impervious rigid containers the amount of dehydrating agent shall be computed by the formula:

$$\text{Pounds of dehydrating agent} = \frac{V}{22000} + \frac{D}{2}$$

where V = volume of container in cubic inches, and D = pounds of dunnage contained therein. Excluding the dunnage from consideration at present, assume a container with a volume of 7,000 cubic inches. One-third pound (about 6 ounces) of silica gel is therefore the specification requirement. Assume now that the package is packed and sealed in a room where the temperature is 130° F. (54° C.) and the relative humidity 60 percent. The

²ANP-13-A, Army, Navy, Aeronautical Specification for preservation and packaging: parts and equipment (General specification 4) October 18, 1944.

container (about 4 cubic feet) will contain approximately 0.015 pound (0.24 ounce) of moisture. If it were desired to reduce the relative humidity to only 20 percent, sufficient gel would be required to remove the moisture contained in the interval between 20 percent and 60 percent relative humidity, which is computed to be 0.16 ounce. In table 5, taken from Specification JAN-D-169², it is shown that Type-II, Grade-A gel adsorbs 10.5 percent of its weight when the relative humidity is 20 percent. The weight of gel required would therefore be $\frac{0.16}{0.105}$ or 1.5 ounces. The formula requires,

however, the use of 6 ounces, and it is evident that the percent adsorption will be considerably less than the 10.5 percent set up for a 20 percent relative humidity. A computation indicates that the 6 ounces of gel will adsorb about 2 percent moisture producing a relative humidity of about 5 percent in the container. An 8-ounce bag, if used, will adsorb about 2 percent of its weight in about 2 hours, and a 1-ounce bag will adsorb about 2 percent of its weight in about 1/2-hour at a temperature of 130° F. (54° C.) and 60 percent relative humidity (figs. 3 and 6). Actually, however, the required time for the gel to adsorb water vapor up to 2 or 3 percent of its own weight is somewhat longer than indicated here; for the relative humidity decreases as the adsorption process continues, and it has been shown that the rate of adsorption decreases with a decrease in relative humidity. The increase in time, however, is relatively unimportant, for the reduction to the 30 percent relative humidity occurs during the earlier time interval.

Example 3 -- Influence of the Volume of Gel in a Flexible Barrier on the Rate of Adsorption of Moisture. -- Existing specifications require that one type of flexible moisture vapor barrier used in packaging work shall have a maximum moisture vapor transmission rate of 0.25 gram per 100 square inches per 24 hours at a differential of 42 millimeters at 100° F. (38° C.) and 95 percent relative humidity. For this type of barrier Specification ANP-13-A recommends that the amount of gel be determined by the formula:

$$\text{Pounds dehydrating agent} = \frac{A}{10} + \frac{D}{2}$$

in which A = area in square feet of moisture barrier, and D = pounds of dunnage enclosed in a package.

To make the comparison with the previous problem simple, assume a package in the shape of a cube with a volume of 4 cubic feet. Each edge would therefore be approximately 1.60 feet long. Ignoring the dunnage, the gel

required would be $\frac{6 \times 1.60^2}{10} = 1.5$ pounds (approx.). It may be seen from a comparison with the other problems that both the percent of gain and the relative humidity are reduced to rather low magnitudes shortly after the package is sealed, and that the time element is reduced accordingly.

The previous discussions indicate, therefore, that if the amount of gel required by Specification ANP-13-A is placed in a package without dunnage

²JAN-D-169, Joint Army-Navy specification. Desiccants (activated) May 8, 1945.

that moisture equilibrium conditions for the amount of moisture sealed in the package at time of closing will be reached in a period of 1 to 3 hours.

Hysteresis

General

Questions have arisen as to the effect of hysteresis on the ability of the gel to function efficiently in a package. For the purpose of discussing this subject, reference is made to the work of Rao (5) in determining the permanence and scanning of the silica gel hysteresis loop. Figures 9, 10, and 11 are reproduced from this article in the Journal of Physical Chemistry to show the characteristics of the loop. In his studies he subjected silica gel to 19 cycles of sorption and desorption in order to determine if the hysteresis loop drifts or retains permanent characteristics. These cycles were made at a temperature of 86° F. (30° C.) at which vapor saturation is reached at a vapor pressure of 1.25 inches (31 millimeters) of mercury. Sorption was accomplished by increasing the pressure by raising the relative humidity from 0 to saturation and desorption by decreasing the pressure. The arrows on the curves indicate the direction of pressure application. A study of the curves indicates: (a) that excepting for the first cycle, the hysteresis loop retains permanent characteristics (fig. 9); (b) that the hysteresis loop does not begin until a relative humidity of 35 percent is reached; (c) that when sorption ends on any part of the loop below the peak, desorption will follow a path that will bring it back to the main desorption curve as indicated by a, b, and c (fig. 10); and (d) that within the loop sorption starting at any point within the loop will not reach the sorption curve but will follow an independent path to the peak (fig. 11).

Influence in Packages

The significance of these characteristics to packaging are self evident. The first scanning may be ignored, since all gel in packages will be subjected to many cycles of sorption and desorption due to changes in relative humidity induced by changes in temperature. Hence, it may be assumed that the adsorption and desorption characteristics are permanent. The most important fact to be gleaned from these curves is that below a relative humidity of 35 percent the adsorption and desorption processes are on the same line. Since packaging procedure requires that the relative humidity within a package be confined to 30 percent or less, confidence may be felt in computations in which moisture content of the gel is used as a determinant of the relative humidity within a package. As a practical example, let it be assumed that the gel from several packages representing a large shipment of units is to be weighed to determine the effectiveness of the gel in maintaining a predetermined relative humidity within the barrier space. If the percent of moisture gain is such as to indicate a relative humidity below 35 percent, the correctness of the indication may be assumed. Assume, however, that on opening a package the temperature is

86° F. (30° C.) and the moisture content of the gel is found to be 23 grams per 100 grams of gel. According to figure 2, for a moisture content of 23 grams the pressure may be 16.5 or 12 millimeters, which for a temperature of 86° F. (30° C.) would indicate a relative humidity of either 53 percent or 39 percent. From the standpoint of packaging work either indication is sufficient to rate the package as poor so that the actual position of the moisture on the loop is unimportant.

Effect of Temperature Changes on the Relative Humidity

Within a Container Without Silica Gel or Dunnage

If it is an accepted fact that steel will rust and corrode in an atmosphere in which the relative humidity of water vapor is in excess of 30 percent, there is a definite reason for the inclusion of a relative humidity agent in packages containing equipment subject to damage by corrosion or rust. Simply sealing a container at a relative humidity at or below 30 percent without the inclusion of such an agent does not assure that the relative humidity will remain at the low safe relative humidity. The relative humidity within a sealed container changes rapidly with changes in temperature, increasing with a decrease of temperature and conversely decreasing with an increase of temperature. For example, if a container packed and sealed at 70° F. (21° C.) and 20 percent relative humidity is allowed to cool to 50° F. (10° C.), the relative humidity within the container will rise from 20 percent to 41 percent, well above the 30 percent accepted as the safe level. If further cooled to 40° F. (4° C.), the relative humidity will rise to 59 percent, and at a temperature of 27° F. (-3° C.) the air in the container will be saturated and sweating will occur within the package. At this lower temperature there will probably be some ice formation within the package.

A graphic example of the relation between relative humidity and temperature within a container that did not contain a water adsorbing agent is given by figure 12, which was copied from a bulletin issued by the Davison Chemical Company (3). The upper curve shows temperature and the lower relative humidity within the container, both being obtained by means of an automatic recording device sealed in the container. The heavy black line between the temperature and humidity curves shows the time period in which the container was sealed at relative humidity of about 70 percent and a temperature of 90° F. (32° C.). At this condition the vapor pressure within the container was 1 inch of mercury. Within a few hours the temperature rose to 94° F. (34° C.) and the relative humidity was reduced to 64 percent which is as shown on the chart. Saturation should occur at a temperature of 79° F. (26° C.) and no increase in relative humidity should be shown upon further lowering of the temperature, which is also indicated on the chart. Particular attention should be centered, however, on the fact shown by the chart that the relative humidity within a container responds rapidly to changes in temperature.

With Silica Gel

Let it be assumed now that a dehydrating agent, such as silica gel, is included in the container and study the effect of temperature changes on the relative humidity within the container. Consider that the container was sealed at a temperature of 70° F. (21° C.) and a relative humidity of 70 percent or at vapor pressure of 0.51 inch of mercury. Sufficient gel is sealed in the container to reduce its relative humidity to 20 percent. At a temperature of 70° F. (21° C.) and a relative humidity of 70 percent, the vapor content of the container is 0.008051 pound, and at 20 percent relative humidity it is 0.0002302 pound per cubic foot, the difference 0.0005749 to be adsorbed by the gel. Figure 2 shows that gel in equilibrium with an atmosphere at 20 percent relative humidity contains 10 percent water. Hence, the weight of gel required per cubic foot would be $\frac{0.0005749}{0.10} = 0.005749$ pound. Let it be assumed now that the temperature

of the package is to be lowered to 40° F. (4° C.). Figure 1 shows that the adsorptive capacity of gel is increased as the temperature is lowered, or as the relative humidity is increased. The saturation content of vapor in a cubic foot at 40° F. (4° C.) is 0.000409 pound. With 0.0002302 pound available the relative humidity at 40° F. (4° C.) would be 57 percent if the gel did not adsorb any more. As the relative humidity is increased, however, the adsorptive capacity of the gel is increased and more of the available moisture is adsorbed until a new point of equilibrium is reached between the moisture content in the gel and the relative humidity in the can. Assume that 50 percent of the available moisture is adsorbed by the gel under the new condition, which will add 0.0001151 pound to that already adsorbed. The total adsorbed moisture is now 0.00069 pound, which is equal to 12 percent of the weight of the gel corresponding to a relative humidity of 25 percent according to figure 2. The free moisture is now 0.0001151, which is 28 percent of the saturated quantity at 40° F. (4° C.). It is likely that a closer balancing of the computation will show the relative humidity within the container to rise from 20 percent to 26 percent with a drop in temperature from 70° to 40° F. (21° to 4° C.). It may be seen, therefore, that the gel will prevent the extreme magnitude of change in relative humidity that were evident in the previous example.

Next, assume that the temperature is lowered to 20° F. (-7° C.). The silica gel is assumed for trial computation to adsorb an additional 0.0001600 pound giving a total of 0.0007349 pound adsorbed vapor. This amounts to 12.9 percent of the weight of the gel giving a required relative humidity in the container of approximately 26 percent. The balance of the free moisture would be 0.0002302 less 0.00016 or 0.0006702 pound. At 20° F. (-7° C.) the container would contain 0.000176 pound of moisture at saturation. Hence, the new relative humidity would be 26 percent, which is in balance with the relative humidity indicated by the silica gel.

These examples were designed to show the condition in a package containing sufficient gel to reduce the relative humidity to 20 percent, as in tight containers or in containers with permeable barriers, which after a long period of service had allowed a sufficient inflow of moisture to raise the relative humidity to 20 percent. It has been shown that, in general, the

amount of gel enclosed in a package with a permeable barrier is sufficient to reduce the relative humidity to about 5 percent, and under this circumstance it can be shown that the changes in relative humidity due to changes in temperature are negligible for all practical purposes. That this is true is also shown graphically by figure 13 copied from a bulletin issued by the Davison Chemical Company (3). The curves have the same significance as in figure 12 except that sufficient gel has now been introduced into the package to reduce the relative humidity within the package to about 5 percent. It may be noted that the 30 percent limit was reached in about 1-1/2 hours. After the gel reached the 5 percent humidity level a lowering of the temperature from 95° to 45° F. (35° to 7° C.) in the early part of the test and from 90° to 35° F. (32° to 2° C.) in the second tests produced hardly a ripple in the relative humidity level.

It may be concluded, therefore, that temperature changes do not seriously affect the relative humidity within a container when a sufficient amount of silica gel is used.

Influence of Dunnage on Moisture Conditions in a Container

Moisture Capacity

As mentioned previously, practically all solids have the property of adsorbing gas. Wood used as dunnage in packages also has this property, and it exerts an important influence on the relative humidity condition within a container. It is evident that wooden material exhibits large surfaces due to its permanent capillary structure and is therefore capable of adsorbing relatively large quantities of water vapor. For wood, as for silica gel, there is a relationship between the relative vapor pressure and the moisture content. They differ, however, in that the sorption-relative humidity curve for wood is a smooth sigmoid curve, while that for gel is practically a straight line up to a relative humidity of 45 percent, the curve then becoming convex to the relative humidity axes through the higher humidity range. Another difference is that the sigmoid curve varies according to whether equilibrium is approached from a higher or a lower vapor pressure, thus producing a hysteresis effect throughout the entire relative humidity range. For convenience of reference figure 14 is reproduced from the book Wood Chemistry (8). It may be noted that the hysteresis effect characterizes these curves throughout the entire range of the curve, while in silica gel the hysteresis effect does not begin until a relative humidity of 35 percent is reached.

As in the silica gel curves, the wood curves show that points obtained by desorption give larger equilibrium moisture-content values than those obtained by adsorption at the same relative vapor pressure or relative humidity. The rate of increase in percentage of moisture content in relation to vapor pressure decreases to a minimum at a relative vapor pressure of about 0.3 to 0.5 and then increases to a maximum at the saturation point. This differs from the gel, which shows an almost constant rate of moisture content change per unit change in relative vapor pressure to about 27 percent

and then a gradually decreasing rate of change to a minimum close to the saturation point.

Effect of Temperature.---Figures 15 and 16 show that temperature effects the equilibrium moisture content of wood at all vapor pressures, the increase in temperature causing a decrease in the equilibrium moisture content at the rate of about 0.1 percent for each increase in temperature of 1° C. at the saturation vapor pressure. A similar linear increase in sorptive power with an increase in temperature exists for each equilibrium relative vapor pressure. Particular attention is called to this characteristic in view of the fact that for all practical purposes the relative humidity-moisture adsorption characteristics of silica gel are independent of temperature effects, as shown by figure 2.

Adsorption-desorption Ratio.---Seborg (6) has shown that the ratio of the adsorptions to the desorption moisture content over a considerable portion of the closed hysteresis loop is a constant, which varies only slightly between different cellulose materials. The range in values of this constant as reported in Wood Chemistry (8) is from 0.76 to 0.89. An average of 0.86 seems appropriate for use in this work.

Action Within a Package -- Wood Only

No data are available as to the effect of wood on the relative humidity in a container when no silica gel is included. By reference to the relative humidity-moisture content curve of dunnage (fig. 14) some idea may be gained as to the effect of the moisture content of dunnage on the relative humidity with a container. Assume that 5 pounds of dunnage is enclosed within a vapor barrier in a package that was sealed at a temperature of 78° F. (26° C.) and a relative humidity of 60 percent. As a basis for further discussion let it be assumed that the wood had also been exposed until its moisture content was in equilibrium with the temperature and relative humidity sealed in the package. Hence, no change will be introduced in the container by the presence of the wood as long as the temperature of the package remains unchanged. On the basis of the 78° F. (26° C.) -60 percent relative humidity, the dunnage when on an adsorptive cycle would contain 10.5 percent of its dry weight in water. Assume now that the temperature of the package is raised to 104° F. (40° C.).

The action that occurs is somewhat difficult to describe, but it may be assumed to be as follows: The relative humidity of the atmosphere in this container tends to lower. The wood undergoes desorption and therefore gives up moisture to the container, thereby increasing its relative humidity above that indicated by the change to the higher temperature. Following the desorptive side of the hysteresis loop, the desorptive action continues until a new equilibrium point is reached.

Consider a numerical example using a volume of 5 cubic feet contained in the barrier. At a temperature of 70° F. (21° C.) and a relative humidity of 60 percent the space within the container contains 0.000888 pound of moisture.

At a temperature of 104° F. (40° C.) and a relative humidity of 60 percent the space contains 0.0093 pound, the difference being 0.008412 pound. By increasing the temperature of the wood from 70° to 104° F. (21° to 40° C.) the equilibrium moisture capacity of the wood at 60 percent relative humidity is reduced from about 10.5 percent to 10 percent. Hence, it is possible for the 5 pounds to lose 0.025 pound of moisture. Only 0.008412 pound are, however, required to reestablish the 60 percent relative humidity within the container. When this amount has been lost there is still a gradient from the wood to the air at the higher temperature; so there is still some loss until equilibrium is established along the 70° F. (21° C.) curve, which is estimated to occur at a relative humidity of 63 percent. Thus the effect of the wood in the container is to prevent the lowering of the humidity as would occur in the container if the wood is not present. It is probable that there is a temporary lowering of humidity, its extent and effectiveness depending on the rate at which the moisture is given up by the wood.

Wood and Silica Gel.---Assume now a duplicate sample that includes the amount of silica gel required by the formula, ANP-13-A, in which the weight of the dehydrant in pounds = $\frac{A}{10} + \frac{D}{2}$. If the package is in the shape of a cube, each edge will be about 1.7 feet long; the area of each side, about 2.9 square feet; and the area for the six sides, 17.4 square feet.

The weight of the dehydrant required is therefore $\frac{17.4}{10} + \frac{5}{2} = 1.74 + 2.5 = 4.25$ pounds, approximately. The action within the container when first sealed at a temperature of 78° F. (26° C.) and relative humidity of 60 percent is now dynamic instead of static as in the previous example. The gel immediately starts reducing the moisture content in the air creating a vapor pressure potential favorable to the loss of moisture from the wood. If the temperature is kept constant, a relative humidity condition is finally produced in the container in which the wood-vapor-silica gel system is in equilibrium, no further loss occurring from the wood and no additional gain being made by the gel. A numerical determination of the final equilibrium point is difficult to make because there is no direct mathematical relationship between the factors inherent in the three components of the system. An approximation can be made, however, by a trial and error method. The assumption is that the wood-gel-air system reaches a common equilibrium point. Assume as a first trial that this point is 15 percent relative humidity. Figure 2 for gel shows that at this relative humidity the gel will have adsorbed 7.5 percent moisture. This means that the gel will have adsorbed 0.075×4.25 or 0.32 pound of water vapor from the air and wood. The air at 78° F. (26° C.) and 60 percent relative humidity contains 0.00888 pound of water, and at 15 percent relative humidity it will contain 0.000525 pound. The gel is therefore assumed to have adsorbed 0.008355 pound, leaving approximately 0.331 to be adsorbed from the wood. Using the 77° F. (25° C.) curve (fig. 15) for Sitka spruce and for convenience following the adsorbent side of the hysteresis loop, it may be seen that at 15 percent relative humidity the percentage of moisture in the wood has dropped from 10.5 percent to 3.5 percent. Since the wood is in a desorbing action, the actual percentage at 15 percent relative humidity will be greater as

determined by dividing 3.5 by 0.86 (which is the adsorbent-desorbent factor), which gives a value of about 4 percent. With this percentage the loss of moisture from the wood will be 0.325 pound, which is approximately equal to the estimated pickup by the gel, thus establishing equilibrium.

For all practical purposes, therefore, it may be said that the action of the gel was to reduce the relative humidity of the system to 7.5 percent.

Temperature Increase.---To carry the problem one step further in the analysis of conditions in a container, assume that the temperature is increased to 104° F. (40° C.). An increase of temperature decreases the equilibrium capacity of wood. A small compensating factor is that the relative humidity of the air in the container is decreased by an increase of temperature. At 15 percent relative humidity the decrease in equilibrium capacity of the wood is about 0.2 percent giving an absolute loss of 0.1 pound of water vapor capacity; hence, the gel is called upon to adsorb an additional amount of vapor until equilibrium is reestablished. Actually, however, the wood only loses a portion of its decreased capacity before equilibrium is reestablished. The amounts involved are too small to use with accuracy on the curves, and they are minute enough to justify the conclusion that for this particular example there will be no measurable change in relative humidity within the container due to a rise of temperature from 78° to 104° F. (26° to 40° C.).

If the temperature is raised to 175° F. (80° C.), the loss in equilibrium capacity of the wood at 15 percent relative humidity amounts to about 1.5 percent involving an absolute loss in capacity of 0.075 pound of moisture. As the loss of moisture continues, the relative humidity of the container increases, which in turn increases the equilibrium capacity of both the wood and the gel. This continues until a new equilibrium point is established. Assume that the new equilibrium is established at 18 percent relative humidity. The silica gel then contains 9 percent of adsorbed water, an increase of 1.5 percent or 0.046 pound above that shown to be true for the 15 percent relative humidity. At a temperature of 175° F. (80° C.) and a relative humidity of 18 percent the wood contains 2.5 percent of its dry weight in water, or an absolute quantity of 0.125 pound. Since at the previous equilibrium condition it was shown to have an absolute quantity of 0.175 pound, the loss is 0.50 pound, which for approximate purposes may be assumed to be equal to the gain in weight shown by the gel. Here again it was shown that even with as extreme a change of temperature as from 78°F. to 175° F. (26° to 80° C.) the change in relative humidity in the container is only 3 percent in the presence of silica gel.

Wood as a Desiccant

General

Wood, if dried to a moisture content of approximately 5 percent or less, will perform desiccating functions similar to those performed by silica

gel, as may be seen from a study of figures 15 and 16, which may be used for the purpose of helping in a fuller discussion of this point. Each curve within figures 15 and 16 is based on an exposure condition in which there is an unlimited amount of moisture available in a practically unlimited space so that the wood can contribute moisture or adsorb moisture from space without affecting the relative humidity of the exposure condition. In a container, however, the space and volume of moisture is limited and any change in the moisture content of the wood will tend to affect the relative humidity of the space. By comparison, however, moisture in the space is an extremely small proportion of the moisture content of the wood. Hence, only minute changes can occur in the moisture content of the wood once equilibrium is established.

Example 1

Assume that 5 pounds of wood have been dried at a temperature of 212° F. (100° C.) so as to contain 2.5 percent moisture. This represents a total of 0.125 pound of moisture. If the wood is sealed into a 1-cubic foot package at a time when the temperature is 70° F. (21° C.) and the relative humidity is 80 percent, the space will contain a total of 0.00092 pound of moisture. If the moisture content of the space at 70° F. (21° C.) were unlimited, the wood would pick up moisture in accordance with the relationship shown in figure 16 and its moisture content would increase until equilibrium was established with the relative humidity of the unlimited space. The supply is limited, however, and it can only take on moisture until its vapor pressure is equal to that in the container. This point of equilibrium can be determined approximately by trial and error computation. A 2.5 percent moisture content of the wood located on the 212° F. (100° C.) curve of figure 16 shows an equilibrium point of about 23 percent relative humidity. Assume that the relative humidity of the package will be reduced to 25 percent when the wood has adsorbed sufficient moisture to reach equilibrium at 70° F. (21° C.). At saturation at a temperature of 70° F. (21° C.) the moisture content of the package would be 0.001151 pound and at 25 percent relative humidity it would be 0.000288 pound. Since the moisture content at 80 percent relative humidity was found to be 0.00092 pound, the wood will have adsorbed 0.00064 pound to reduce the relative humidity of the container to 25 percent. Adding 0.00064 pound to the original 0.125 gives a total of 0.1256 pound of adsorbed moisture or an increase from 2.50 percent to 2.51 percent at a temperature of 70° F. (21° C.). Actually, however, the equilibrium moisture capacity of wood increases with a decrease of temperature (as shown by the curves in figures 15 and 16), so that this first determination is in error. Following the 23 percent curve leftward towards its intersection with the 70° F. (21° C.) line, it is found that the moisture content would have had to increase to about 5 percent to maintain the 23 percent relative humidity. It is apparent from the condition imposed on the container in this example that the entire moisture content of the air in the space of the package would have been sufficient to raise the moisture in the wood to only about 2.52 percent. It is evident therefore that the equilibrium point lies at the intersection of the 70° F. (21° C.) curve with the 2.52 percent moisture content line. Following the 70° F. (21° C.) curve to this

percentage it may be seen that the effect of the wood in this problem is to reduce the relative humidity of the space within the package to about 10 percent.

Example 2

The preceding example was used to illustrate one extreme condition. Consideration will not be given to a moisture content of about 4 percent in the wood which can be maintained at temperatures ranging from 70° to 110° F. (21° to 43° C.) and a relative humidity of 20 percent. With this relative humidity wood can lose moisture in a container due to a rise of temperature from 70° F. (21° C.) to as high as 175° F. (80° C.) without causing the relative humidity within a container to exceed the 30 percent safe relative humidity point. Assume the same dimensions of container and weight of dunnage as in the previous problem but a relative humidity of 80 percent at a temperature of 80° F. (27° C.). Let the dunnage be sealed in when it contains 4.3 percent moisture at a temperature of 80° F. (27° C.) which indicates an equilibrium relative humidity of 23 percent. While reaching equilibrium at 80° F. (27° C.) it will adsorb moisture from the confined package space until a new equilibrium is reached. The wood when first inserted will contain 0.215 pound of moisture. If it adsorbs 0.00087 pound from the package space, it will reduce the relative humidity of the space to 25 percent and will increase its own water content to 0.21587 or 4.33 percent moisture content. The equilibrium relative humidity would be about 21 percent. It is probable that a further balancing computation would show the relative humidity of the container to be only slightly more than 21 percent once equilibrium was reached. In no case would the equilibrium relative humidity at this temperature be changed appreciably even if it were possible for the wood to adsorb all the moisture originally present in the confined space of the container.

Temperature Rise.---If after equilibrium is reached the temperature within the container is raised, the equilibrium capacity of the wood for moisture will be decreased. If it is raised from 80° to 150° F. (27° to 66° C.) in an unconfined space with a relative humidity of 21 percent, the equilibrium capacity will be reduced to approximately 3.2 percent. In a confined space, such as in the previous example, the wood will give off moisture, thereby increasing the relative humidity of the space, which in turn increases the capacity of the wood. This process continues until a new equilibrium is established. It is evident that only a slight loss of moisture from the wood is necessary to affect an appreciable change in the relative humidity of the container. For all practical purposes it may be assumed that the percentage of moisture available in the wood at 80° F. (27° C.) will determine the relative humidity of the container at 150° F. (66° C.). Following a horizontal line representing 4.33 percent moisture content until it intersects the 150° F. (66° C.) curve (fig. 16) it may be noted that the new equilibrium in the container will occur at a relative humidity of about 29 percent. It is evident that at still higher temperatures the relative humidity of the container would increase above the 30 percent limiting relative humidity. It will be shown, however, that a temperature in excess of 150° F. (66° C.) in a container is a highly improbable event.

Example 3 (Flexible Barriers)

It may be assumed that wood containing not more than 4 percent moisture can be used as a desiccant in rigid containers into which there is no inflow of moisture from the atmosphere. For flexible barriers the maximum amount of moisture allowable should be closer to 2.5 percent thereby allowing the wood the leeway necessary to adsorb moisture up to about 4 percent. In the previous example 5 pounds of dunnage was used in the package, and it was tacitly assumed that the barrier was completely impervious. Assume now that the barrier is flexible and that it has a maximum transmission rate of 0.25 grams per 100 square inches in 24 hours (Type III JAN-P-116). If the moisture content of the dunnage when first put in the package is 2.5 percent and the maximum amount of moisture allowable is 4 percent, it can gain 0.075 pound of moisture between the limits, which is equal to about 34 grams. Assume that the flexible barrier has an area of 864 square inches. Then if all events are favorable to the occurrence of the maximum transmission rate, an unlikely probability, the wood will increase from 2.5 to 4 percent moisture content in about 16 days. To give this particular package a year of useful life would require the use of about 20 times as much dunnage as given in the example.

Specification JAN-P-116⁴ requires that $0.7A + 1D$ pounds of Type III and V Grade C desiccant be used in a package with a Type III barrier. In this formula, A = area in square feet of moisture barrier and D = pounds of dunnage enclosed within the barrier. For comparative purposes the amount of desiccant is computed by means of the formula. The area of the package is 6 square feet; hence, the amount of desiccant required is $0.7 \times 6 + 1 \times 5 = 9.2$ pounds, which added to the dunnage gives a total of 14.2 pounds. For Grade C desiccant, Specification JAN-D-169 requires a moisture content of about 7 percent for a relative humidity of 30 percent. In order to account for the moisture flowing into the package through the barrier, the first part of the formula, or $0.7A$, is used, which gives a total of 4.2 pounds of desiccant. Its capacity up to 30 percent relative humidity is therefore 4.2×0.07 or 0.294 pound, or 131 grams, of moisture. On the basis of the maximum transmission rate of moisture vapor through the barrier the useful life of the package will be about 61 days. If wood is added so as to weigh a total of 14.2 pounds and no other desiccant is used, the moisture increase between 2.5 percent and 4 percent is 0.213 pound, and the useful life of the package increases to 42 days. To provide a useful life of 61 days, the amount of the desiccant must be increased to 21.5 pounds. From the standpoint of weight the advantage is therefore with the desiccant.

Type-I Flexible Barrier

If a type-I barrier in which the transmission rate is 0.05 grams per 100 square inches per 24 hours were used, the useful life of the package with 5 pounds of wood dunnage would be increased to about 80 days. The JAN-P-116

⁴JAN-P-116, Joint Army-Navy specification, packaging and packing for overseas shipment, preservation, methods of. May 8, 1945.

formula for the amount of Grade C desiccant required in a package with a type-I barrier is $(0.2A + 1D)$, which indicates a useful life of about 88 days. On the basis of the formula the desiccant required for the moisture transmission through the barrier is 1.2 pounds; that required for the moisture in the wood, 5 pounds. With the wood the total weight is about 11.2 pounds. Instead of desiccant, let it be assumed that 6.2 pounds of wood at a moisture content of 2.5 percent is added. The total weight of dunnage can now adsorb 0.15 pounds of moisture, which will give the package a useful life of 154 days.

It is evident therefore that the more impervious the barrier, the more likely it is that dried wood can replace other desiccants in packages. Since dunnage is necessary in many packages, the only added expense is that of drying.

The ability of wood to act as a desiccant is recognized by formula 2 in JAN-P-116, which is used for the determination of the weight of desiccant required in rigid containers, such as metal cans.

For containers having a volume greater than 100 cubic inches formula 2 is as follows:

$$\text{Pounds of desiccant} = \frac{V}{22000} + 0.06D (M-4)$$

in which M = moisture content of dunnage in whole numbers, D = pounds of dunnage contained in package, and V = volume of container in cubic inches. The first part of the formula gives the weight of desiccant required to reduce the relative humidity of the atmosphere in the container to below 30 percent, and the second part gives the amount required to reduce the moisture content of dunnage to 4 percent or less. It should be noted that if the moisture content of the dunnage is 4 percent, no gel is required for the second part of the formula. If the moisture content goes below 4 percent, it is possible to eliminate the use of desiccant entirely, since the second part of the expression would become negative. This is in line with previous reasoning in the paper, with the exception that it is believed that no desiccant is required in a rigid container when the moisture content of the dunnage is at or below 4 percent.

Discussion

There are certain disadvantages to the use of dunnage as desiccants in packages with flexible barriers. In general, the dunnage is fixed or fastened to the packed article, and its replacement at the end of its useful life as a desiccant involves some difficulties. This is especially true if the dunnage has special shape and replacement is necessary in a location where no replacement facilities are available. In tight containers, such as metal cans, this is not a consideration, and dried wood can be used as effectively as special desiccants.

Rate of Change of Temperature

The mathematical determination of the rate of change of temperature within a package due to changes in external or atmospheric temperatures is a rather difficult procedure due to the many factors involved. The air gap between the item packed and the walls of the containers, the materials of the inner and outer container, air currents within the container, and the shape, mass and material of the packed item are factors that combine to determine the rate of gain or loss of heat; and as a general rule practically nothing is known of the magnitude of some of these factors by the packaging engineer. In order, however, to obtain some indication of the time required for a package to gain or lose heat several tests were made.

Test No. 1.--A thermometer was inserted half way through a hole in the top of an empty sealed metal container (10-5/8 inches in diameter and 16-5/8 inches deep), and the assembly was placed in a room that raised the temperature of the inside of the container to 136° F. (58° C.). After it reached the temperature of 136° F. (58° C.), it was placed under a water spray. The temperature of the water was 66° F. (19° C.) at the start of the test and dropped to 60° F. (16° C.) in an hour and continued at this temperature for the rest of the test. Temperature readings were obtained and recorded at regular intervals.

Test No. 2.--A hair latex mold with a center void was packed into a metal container of the same size so as to occupy about two-thirds of the volume of the container. The container was then sealed and a thermometer inserted half way through the top so that the mercury bulb occupied a position in the center void of the latex. The container was allowed to stand in a room until it reached a steady temperature of 68° F. (20° C.). It was then placed in a hot room until the temperature within the container registered 134° F. (57° C.). Readings of temperature were made at regular intervals. The container was then removed and allowed to cool in a room in which the temperature varied between 67° and 72° (19° and 22° C.). Readings were taken at regular intervals during the cooling period. The container was then replaced in the hot room until a temperature of 132° F. (56° C.) was reached. It was then placed under a water spray at 60° F. (16° C.) and allowed to cool, readings again being taken at regular intervals.

Test No. 3.--The latter part of test No. 2 was repeated with latex hair.

Test No. 4.--A thermometer was inserted half way through the top of a metal container (10-5/8 inches in diameter and 16-5/8 inches deep) containing a generator weighing about 35 pounds, about 2-1/2 pounds of wood dunnage, 1/2 pound of creped cellulose wadding, and 125 grams of silica gel. The assembly was allowed to cool until the inside temperature reached 70° F. (21° C.). It was then placed and kept in a hot room until the temperature reached 120° F. (49° C.), readings of temperature being obtained at regular intervals. It was then removed to a room with a temperature of 70° F. (21° C.) and allowed to cool. The test was then repeated allowing the inside of the can to reach a temperature of 140° F. (60° C.) and then cooling it with a water spray at a temperature of 64° F. (18° C.).

The results of the four tests are given in tables 6 through 9.

Temperature Changes in Sunlight Exposure

Some studies were also conducted to determine temperature conditions within a container exposed to the direct sunshine in the open. These tests were made in an attempt to determine the maximum possible temperature within a container under natural exposure conditions and formed a part of the larger study designed to study the influence of temperature changes on the relative humidity within a container. Since these effects have already been discussed, only the temperature data will be given and interpreted here.

The test procedure consisted of observing the temperature of a set of containers exposed to sunshine into which thermometers were inserted and at the same time recording shade temperature in the vicinity of the containers. No specific correlation could be found between shade temperature and container temperature. Wind and convection currents are, of course, an important influence on the temperature of the walls of a container, and these factors were not measured during the test. In general, however, the test showed that on clear days the temperature of the inside of the container averaged about 25° F. (14° C.) higher than the temperature indicated by the shade thermometer. On a clear day with the shade temperature at 70° F. (21° C.) six containers exposed to the sun showed temperatures as follows: 74°, 89°, 90°, 86°, 78°, and 85° F. (23°, 32°, 32°, 30°, 26°, and 29° C.). When the shade temperature was 80° F. (27° C.) the same containers showed temperatures of 100°, 99°, 100°, 102°, 99°, and 103° F. (38°, 37°, 38°, 39°, 38°, and 39° C.).

At a shade temperature of 97° F. (36° C.), the readings for the inside of the containers were 126°, 124°, 125°, 128°, 123°, and 127° F. (52°, 51°, 52°, 53°, 51°, and 53° C.).

The indications, therefore, are that at the higher shade temperatures there is a somewhat greater difference between the shade and container temperatures. This is probably due to the fact that on extremely hot days the atmosphere is usually clear, and the hot periods of the days are characterized by an almost complete absence of wind currents, thus enabling the direct heating of the container with a minimum of cooling due to wind movement. It is believed that the data gathered during these tests may be used in estimating the probable maximum temperature on the inside of a container.

The 1941 Yearbook of Agriculture reports that the highest shade temperature ever recorded anywhere on the earth is 136° F. (58° C.) recorded at Azizio, Libya, North Africa, on September 13, 1922. The average difference between shade temperature and container temperature noted during the hotter days is about 30° F. (17° C.). Applying this differential to the temperature of 136° F. (58° C.) it may be estimated that 166° F. (74° C.) is the maximum probable temperature that can be expected to occur within a metal container. Temperatures approximately 136° F. (58° C.) are rare occurrences, and the Yearbook mentions only three other places in which a shade temperature in excess of 125° F. (52° C.) has been recorded.

Temperature changes within a container are not uniform throughout the space within the container. Convection currents on the outside and inside of the container due to differences of temperature are set up and tend to maintain air circulation. If two sealed containers are exposed to the sun and a thermometer is placed in one container near the side facing the sun and in the other on the opposite side, the thermometer on the sun side will usually register higher temperatures than the other. Differences as high as 5° F. (3° C.) were found in the tests. This is a favorable condition in a package, since a difference of temperature on two sides of a package indicates air circulation, which increases the rate at which moisture can be adsorbed by desiccants.

Permeable Barrier Material

General

Reference is made throughout the text to the use of more or less permeable material as barriers in packaging work. It is believed therefore that a brief discussion of the influences that determine the permeability of these materials will be of value in the discussion as a whole.

Permeability Test

A moisture vapor barrier is used in packaging for the purpose of limiting the entrance of moisture-vapor to predetermined rates as defined by a permeability constant, which will be referred to as "P" in future references. This constant is determined by a standard test, the details of which are outlined in Specification JAN-P-131.⁵ Briefly described, a sample of barrier material is sealed over a test dish containing calcium chloride. The assembly is then placed in a vapor transmission cabinet in which a relative humidity of 90 to 95 percent is maintained at a temperature of 100° F. (38° C.). The dish is weighed at 24 hour intervals until two consecutive weighings indicate that a practically constant rate of vapor transmission has been attained.

Permeability Limits

The unit for the permeability constant in Specification JAN-P-131 is the number of grams of moisture per 100 square inches per 24 hours. The specification also sets up three types of barriers with a transmission rate or permeability factor, which is not to be exceeded for each type. The three types and the limiting rates are as follows:

⁵JAN-P-131, Joint Army-Navy specification, packaging and packing for overseas shipment. Barrier material-moisture vaporproof, flexible. October 31, 1944.

| | |
|----------|------------------------------|
| Type I | 0.00 to 0.05, inclusive |
| Type II | Over 0.05 to 0.15, inclusive |
| Type III | Over 0.15 to 0.25, inclusive |

Permeability Formula

It may be noted that the transmission rates listed in the preceding paragraph are based on an experimental procedure that holds the temperature and relative humidity constant, and that no attempt is made by the specification to list these values as constants of the material. This is due to the fact that in some materials the transmission rate, or permeability constant, varies with both humidity and temperature while in others, the temperature is the only cause for a variation in value.

Aiken, Doty, and Mark (1) state that at a given temperature it may be expected that the quantity of moisture Q that will pass through a barrier can be expressed by the formula

$$Q = P \frac{a}{l} t \Delta p \quad \dots\dots\dots (1)$$

in which a is the area, l the thickness of the material, Δp the pressure difference, and t the time. P is the proportionality constant, which was previously referred to as the permeability constant and characterizes the ability of the material to resist the transmission of water vapor.

Influence of Thickness

Experimental work by Aiken, Doty, and Mark (1) verifies the fact indicated by formula 1 that the value of P is independent of thickness for homogenous materials, such as polythelene, plasticized polyvinyl chloride, and koroseal. Taylor, Hermann, and Kemp (7) have demonstrated this to be true also of polystrene.

The relationship is not valid, however, for materials that are poor barriers, but that are coated with a substance to reduce their transmission rates. Cellophane with a coating of wax is a sandwich-like barrier of this type. The explanation given by Aiken, Doty, and Mark (1) for this behavior of sandwich-like barriers is that the impedance to flow is offered by the coating with but a negligible contribution by the relatively thick foundation material.

Influence of Pressure

Aiken, Doty, and Mark (1) point out that water vapor permeability of a material made of an organic polymer is determined by two factors: (1) the density and configuration of molecular arrangement; and (2) the hydrophilic or hydrophobic nature of the polymer. The permeability factor should therefore be a property of the material and should be independent of the gas pressure gradient. If the polymer is hydrophobic, the factor should be a

true constant and should be applicable under all conditions of flow. If the polymer is hydrophilic or in between, the factor will change due to changes in the solid as a result of vapor sorption.

These first general assumptions are verified by the work of Aiken, Doty, and Mark (1) in which they indicate that P is independent of pressure difference for such materials as Saran, pliofilm, polyethylene, and polyvinyl chloride, which are not unusually hydrophilic. For such hydrophilic material as rubber and cellulose the permeability constant increases with an increase in relative humidity. For uncoated cellulose, and unplasticized cellulose sheeting an increase in the relative humidity from 19 to 85 percent showed that the permeability constant was increased 25 times. Tests on moistureproof cellophane showed a twofold increase in the value of P when the relative humidity was increased from 21 to 82 percent.

In an analysis of the application of formula (1) to the calculation of the permeability constant Barkas (2) has concluded that the reason for the failure of P to remain constant lies in the failure to recognize the fact that formula (1) may not be applicable to the type of flow actually occurring through the material.

Apparently, if an appreciable part of the flow is through an adsorption action of the material and the other part through the openings in disordered layers of molecules, formula (1) cannot be expected to yield consistent results. The values of P obtained from the use of this formula will then be influenced by the relation between the adsorptive capacity of the material and relative humidity.

If use is to be made, therefore, of the permeability constant of a barrier in predicting the useful life of a desiccant, consideration must be taken of the nature of the barrier material. The test procedures for the determination of the transmission rate provide a relative humidity of 90 to 95 percent, which is usually higher than the average obtainable under actual exposure conditions. Estimates based on the test rates are therefore likely to under estimate the useful life of a package provided with desiccant protection. While in some instances the expense of providing desiccant protection is therefore increased, it may in some cases be considered a worthwhile safety factor.

Permeability-temperature

The previous discussion indicates that P as determined by the adopted experimental procedure and as computed by formula (1) may or may not be constant under all types of flow conditions. It was indicated, however, that for homogenous material which is hydrophobic, the value of P is independent of the thickness of the material and the pressure difference. In other words, the value of P may then be considered as a true property of the material.

Of importance is the fact indicated by available data that even in these materials the value of P varies with temperature. Aiken, Doty, and Mark (1) in investigating the relationship between P and temperature for a number of

materials found that in every case the value of P is an exponential function of absolute temperature just as is the vapor pressure of a liquid. They show this relation to be

$$P = P_0 e^{-E/RT} \dots\dots\dots (2)$$

where P is the permeability constant at temperature T° absolute, R is the gas content equal to 1.985 and E, referred to as the energy of activation, governs the sensitivity of the permeability constant to temperature.

Between temperature of 0° to 60° C. (32° to 140° F.) Aiken, Doty, and Mark (1) found the permeability constant of polythene to increase from about 50 percent for a 10° C. (50° F.) change in temperature in the lower temperature ranges to about 200 percent in the higher ranges. They also found this same degree of variation for several other materials.

The practical application of data on the influence of temperature on the permeability constant of a barrier material lies in estimates as to the probable useful life of a package, which is to be subjected to consistent higher or lower temperature than the 100° F. (38° C.) used in the standard permeability test. It can also be useful in the design of packages which are to be subjected to special temperature conditions. The simplest method of obtaining the relation between P and T is to plot the data so as to obtain a straight line.

When P is plotted against $\frac{1}{T}$ on semilogarithmic paper a straight line curve results that can be extended to the temperature under consideration. It will be necessary to make experimental determinations of P at two or more values of T to enable plotting a graph.

Comparisons

Comparisons of the permeability of two materials are of value only at the test temperature. The comparison value may be entirely different at a higher or lower temperature.

Conclusion

A study of the literature on the flow of moisture through permeable barriers indicates a lack of understanding of the laws governing the flow of vapors through materials. It is suggested that additional studies are necessary if a fuller comprehension of the fundamental of vapor transmission through barriers is desired.

Packages with Gel and Dunnage at Extreme Low Temperatures

General

The question has often arisen as to what effect the instrument or unit packed within a container has on the atmospheric conditions within the container when the package is subjected to an extreme lowering of temperature. It is well known that changes in temperature of masses of material are not as rapid as changes which occur in the surrounding atmosphere in which they are exposed. The rate of change is dependent on the specific heat of the material, its mass, and the temperature gradient to which it is exposed. The question as to whether an instrument packed in a container has an influence on the atmospheric condition within the container can be answered by saying that it does.

A specific problem arises, however, by the following assumption. If an instrument is transported in an airplane where it is subjected to extreme cooling, will it cause condensation when the relative humidity of the atmosphere within the container is increased to the dew point. Such a condition may occur if the rate of cooling is considerably faster than the ability of the desiccant to adsorb moisture. The details of the action within the container under this condition can be examined in detail.

Temperature at High Altitudes

Containers which are transported by air will undergo extreme lowering of temperatures. The temperature of the atmosphere reduces with an increase in altitude at an average rate of about 3.57° F. (1.98° C.) per 1,000 feet. This gradient is practically constant from sea level to an altitude of about 35,300 feet, and so far as is known the temperature remains constant at greater altitudes. On the basis of the temperature gradient a package leaving the ground at a temperature of 70° F. (21° C.) will have its temperature reduced to 17° F. (-8° C.) if flown up to an altitude of 15,000 feet.

Ordinary Temperatures

Consider a package similar to that used in Test No. 4 (table 9). The unit is a generator packed within a metal container with a diameter of 10-1/2 inches and a depth of 16-5/8 inches. The volume of the container is 1,438 cubic inches, or approximately 0.82 cubic feet. It contains 3 pounds of dunnage including the cushioning material. Let it be assumed that the package is sealed at a temperature of 80° F. (27° C.) and a relative humidity of 80 percent. An amount of Type III, Grade C silica gel required by formula 2 of JAN-P-116 is included in the package. The formula is: pounds of desiccant = $\frac{V}{22000} + 0.06(M-4)$. It is assumed that the moisture of the dunnage is in equilibrium with an atmospheric temperature of 80° F. (27° C.) and a relative humidity of 80 percent, and according to figure 16 the dunnage will contain about 16 percent moisture. The amount of silica

gel required is therefore = $\frac{1438}{22000} + 0.06D(16-4) = 0.066 + 2.16$. For

Grade C desiccant the results of the formula are multiplied by two, therefore, the pounds of desiccant required are = $0.132 + 4.32 = 4.45$ or 4.5 pounds approximately. When the package is sealed it is allowed to stand a sufficient length of time to establish equilibrium within the package. If it is assumed that the package remains at approximately 80° F. (27° C.) until equilibrium is reached the following action takes place.

The container space contains 0.001169 pound of moisture, and the wood contains 0.48 pound giving a total of 0.481169 pound. According to JAN-D-169 the Type III, Grade C desiccant will be able to adsorb 7.2 percent of its weight in moisture when relative humidity is 30 percent. This will allow the desiccant to adsorb 0.32 pound of moisture, which it will obtain both from the dunnage and the atmosphere within the container. This leaves a total of $0.48 - 0.32$ or 0.16 pound of moisture in the dunnage, which is equal to 5.3 percent moisture content. According to the 80° F. (27° C.) line in figure 16 wood will contain 5.2 percent moisture at a relative humidity of about 28 percent and a temperature of about 80° F. (27° C.). This first approximation indicates that an equilibrium point will probably be reached at a relative humidity of about 29 percent.

At an Altitude of 15,000 Feet

Let it be assumed that the gel and dunnage are in equilibrium with the atmosphere in the container and that it is now to be transported by an airplane flying at an elevation of 15,000 feet.

When brought to the airplane, the package has a temperature of 80° F. (27° C.) and when it is raised to a height of 15,000 feet its temperature drops approximately 56° F. (31° C.) (3.7×15), reducing its temperature to 24° F. (-4° C.). It may be estimated that the airplane will reach the 15,000-foot altitude in about 20 minutes. Assume that it is required to determine the time required for the contents of the package to cool to approximately 24° F. (-4° C.). Test No. 4 gives an indication of the time. With a temperature gradient of 56° above 64° F. (31° above 18° C.) the starting temperature would be 120° F. (49° C.) and the decrease from 120° to 74° F. (49° to 23° C.) a drop of 44° F. (26° C.) required a period of about 4-1/2 hours. Hence, it may be estimated that at least 7 hours would be required for the container to drop 56° F. (31° C.) to the 24° F. (-4° C.) temperature which was estimated for the higher elevation. The drop is more rapid in the earlier stages of the change. A drop of 40° F. (22° C.) is estimated to occur in the first 2-1/2 hours on the basis of Test No. 4.

The action within the container while the temperature change is taking place is as follows: At the temperature of 80° F. (27° C.) and 29 percent relative humidity the atmosphere in the container had a moisture content of 0.0038 pound. This volume, if unaffected by the action of the gel and dunnage, would become saturated at a temperature of about 38° F. (3° C.), and at a still lower temperature free moisture would become available. The reduction to the temperature of 38° F. (3° C.) will, however, require about 3 hours of time giving considerable opportunity for the desiccant and wood to act.

As the relative humidity of the atmosphere in the container is increased, the capacity of the gel is increased. In view, however, of the small volume of moisture in the atmosphere of the container the full capacity of the gel need not come into action. At the temperature of 24° F. (-4° C.) the saturation capacity of air is 0.000222 pound per cubic foot, and at 29 percent relative humidity air contains only 0.0000666 pound per cubic foot. For the particular container, therefore, the content at 29 percent will be 0.000053 pound. It is apparent that the desiccant can adsorb this amount without any noticeable change in percentage adsorption. It was shown that the desiccant adsorbed about 0.3 pound of water at a relative humidity of 29 percent. Hence, the change introduced by the addition of 0.000053 pound would hardly be ascertainable by any known method.

Furthermore, the equilibrium capacity of wood increases as the temperature is lowered; hence, the wood will also tend to adsorb part of the moisture in the container. This tendency of the wood to increase in adsorptive capacity can be determined by an inspection of figures 15 and 16.

It is evident that no detailed discussion is necessary to show that the wood and desiccant will adsorb moisture from the atmosphere within the container as rapidly as the relative humidity is raised due to a lowering of temperature. This statement can be based strictly on the fact that only the adsorption action of the gel and desorption actions of wood involve comparatively minute quantities of container atmospheric moisture and that temperature changes within a container involve comparatively long periods of time. In the example under consideration the maximum possible amount of moisture to be adsorbed by the gel is 0.000013 pound if it is assumed that all available moisture above a relative humidity of 29 percent is to be taken by the gel. This represents a change of about 0.0003 percent in weight of the gel. If 8-ounce bags are used, it can be shown that a period of about 110 hours will be required for an 8-ounce bag to increase its moisture content from 7 to 8 percent when exposed to 80° F. and 30 percent relative humidity. It is evident that a gain of only 0.0003 percent will occur in a period considerably less than 1 hour, which verifies the statement made previously.

This analysis indicates, therefore, that packages as protected against corrosion under ordinary temperatures by the use of desiccants will remain safe when subjected to extreme lowering of temperatures.

Discussion

In the previous pages, consideration was given to the various properties of silica gel and dunnage which influence the moisture conditions within a package. Consideration was given not only to the equilibrium condition, which has been the usual approach to the determination of moisture conditions within a package, but also to the dynamic condition that occurs during changes. The available basic information presented is sufficient for the analysis of humidity conditions to be expected in a package when subjected to extreme changes of temperature. The information also can be valuable in other respects. For instance, the data on the time required for various-sized

packages of desiccant to reach equilibrium may be used in estimating the safe period of time for loading gel into a package. The economics of loading gel into a package may be a determining factor in packaging estimates during peace periods, and time may be an important element during war intervals. It was shown by use of figures 3 through 8 that 1-ounce bags should be loaded into sealed packages immediately after removal from their sealed container. Otherwise they would lose an appreciable percentage of their effectiveness. The time element for 8-ounce bags is not so important.

The data can also be put to use in tracing some of the troubles that are encountered when examining packages. For instance, packages that had been shipped from a factory and are newly arrived at the depot may show high relative humidity conditions as shown by indicators. No conclusion should be drawn from the fact that the package is faulty until a thorough investigation is made. First, information should be obtained as to the temperature at which the package was sealed, and second, as to the temperature at which it was allowed to reach equilibrium. If the package is sealed and stored immediately at a low temperature, say below 30° F. (-1° C.), the time required for equilibrium to be established may be longer than the shipping time. The indicator, because of its larger surface area compared to its weight, takes on moisture at a considerably faster rate than the desiccant and thereby indicates the relative humidity within the container more rapidly than the desiccant. When first sealed, the indicator may not show the equilibrium of the silica-gel-damage-moisture system. The actual conditions within the container can, however, be approximated by the use of the data contained in this report.

Although some data are available on the rate of adsorption or desorption of vapor by wood, the indications are that no particular advantage will be gained by attempting to apply these data to this problem. It was shown in the study that once initial equilibrium is established that future changes in humidity within a container due to temperature changes are of minute magnitude involving time periods of less than one hour, which apparently obviates the necessity for a knowledge of moisture rate changes in wood. The time element can be controlled at will by the use of a predetermined weight of desiccant.

The body of the text contains numerous examples. The extensive use of the numerous examples used in this report was prompted by the desire to cover all conditions and to enable other students of the subject to duplicate the results in actual practice.

The analysis of available data indicates that no further study of the influence of temperature on a package with a rigid container is needed. It is desirable, however, to study the factors that influence the permeability rates of the permeable barriers.

Literature Cited

- (1) AIKEN, W. H., DOTY, P. M., and MARK, H. "Water Vapor Permeability -- What It is and How It Works." Modern Packaging, 18:12:137 (1945).
- (2) BARKAS, W. W. "The Calculation of a Permeability Constant Applicable to Vapor Flow in Solids." Department of Scientific and Industrial Research, Forest Products Research Laboratory, Princes Risborough, England. (1945).
- (3) Davison Chemical Corp., Baltimore, Md., Report.
- (4) DEHLER, F. C., Davison Chemical Corp., "Silica Gel -- Its Use as a Dehydrating Agent." Presented at George Washington University, Washington, D. C. (1941).
- (5) RAO, B. S. "Hysteresis in Sorption." J. Phys. Chem., 45:513 (1941).
- (6) SEBORG, C. O. Ind. Eng. Chem., 29:169 (1937).
- (7) TAYLOR, B. L., HERRMANN, D. B., and KEMP, A. R. Ind. Eng. Chem., 28:1255 (1936).
- (8) WISE, L. E. Wood Chemistry, Rheinhold Publishing Corp., New York (1944).

—

Table 2.--Time required for silica gel placed in open top No. 2-1/2 metal cans to reach equilibrium when exposed to various exposure conditions of temperature and relative humidity

| Amount and form of silica gel | Time required for silica gel to reach equilibrium when exposed to: | | | | | | | | | | | | | |
|--------------------------------|--|-------------|-------------|-------------|-------------|-------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| | 130° F. - 60 | 80° F. - 97 | 80° F. - 80 | 80° F. - 65 | 80° F. - 30 | 40° F. - 94 | percent relative humidity | percent relative humidity | percent relative humidity | percent relative humidity | percent relative humidity | percent relative humidity | percent relative humidity | percent relative humidity |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | | | | | | | | |
| 1-ounce muslin bags | 24 | ..... | 52 | 80 | 85 | 90 | | | | | | | | |
| 2-ounce muslin bags | 30 | ..... | 75 | 115 | 90 | 140 | | | | | | | | |
| 4-ounce muslin bags | 50 | 200 | 135 | ..... | 180 | 490 | | | | | | | | |
| 8-ounce muslin bags | 95 | 250 | 380 | ..... | 250 | 2450 | | | | | | | | |
| 2-ounce loose with- out bag | 12 | ..... | 60 | 85 | ..... | 120 | | | | | | | | |
| 4-ounce loose with- out bag | 35 | ..... | 110 | 135 | ..... | 220 | | | | | | | | |

¹Incomplete at 180 hours.

²Incomplete at 450 hours.

Table 3.--Time required for silica gel placed in open-top No. 2-1/2 metal cans to adsorb 10 percent of its weight when exposed to various conditions of temperature and relative humidity

| Amount and form of | | Time required for silica gel to adsorb 10 percent of its weight when exposed to: | | | | | | | | | | | | | | |
|--------------------|--|--|----------|----------|---------------|----------|----------|---------------|----------|----------|---------------|----------|----------|---------------|----------|----------|
| | | 130° F. - 60: | | | 80° F. - 97 : | | | 80° F. - 80 : | | | 80° F. - 65 : | | | 40° F. - 30 : | | |
| silica gel | | percent | relative | humidity | percent | relative | humidity | percent | relative | humidity | percent | relative | humidity | percent | relative | humidity |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | : | : | : | : | : |
| | | : | : | : | : | : | : | : | : | : | : | | | | | |

¹Incomplete

Table 4.--Percentage of moisture adsorbed by silica gel placed in open-top No. 2-1/2 metal cans at the end of 5 hours when exposed to various conditions of temperature and relative humidity

| Amount and form of | | Moisture adsorbed by silica gel at the end of 5 hours when exposed to: | | | | | | | | | | | | | |
|---------------------|--|--|----------------|----------------|----------------|----------------|----------------|--------------|----------|--------------|----------|-------------|----------|----------|----------|
| | | 130° F. - 60: | | 80° F. - 97: | | 80° F. - 80: | | 80° F. - 65: | | 80° F. - 30: | | 40° F. - 94 | | | |
| silica gel | | percent | relative | percent | relative | percent | relative | percent | relative | percent | relative | percent | relative | percent | relative |
| | | humidity | humidity | humidity | humidity | humidity | humidity | humidity | humidity | humidity | humidity | humidity | humidity | humidity | humidity |
| | | (2.71 inch Hg) | (1.03 inch Hg) | (0.82 inch Hg) | (0.66 inch Hg) | (0.30 inch Hg) | (0.22 inch Hg) | | | | | | | | |
| (1) | | (2) | (3) | (4) | (5) | (6) | (7) | | | | | | | | |
| | | Percent | Percent | Percent | Percent | Percent | Percent | Percent | Percent | Percent | Percent | Percent | Percent | Percent | Percent |
| 1-ounce muslin bag | | 18.5 | 10.5 | 8.5 | 4.8 | 2.5 | 5.0 | | | | | | | | |
| 2-ounce muslin bag | | 15.0 | 9.0 | 7.5 | 4.5 | | 4.5 | | | | | | | | |
| 4-ounce muslin bag | | 11.0 | 3.8 | 3.5 | 2.8 | .9 | 1.7 | | | | | | | | |
| 8-ounce muslin bag | | 8.5 | 3.0 | 2.5 | 1.5 | .4 | 1.0 | | | | | | | | |
| 2-ounce loose with- | | | | | | | | | | | | | | | |
| out bag | | 21.0 | 8.0 | 6.0 | 3.0 | 1.8 | .3 | | | | | | | | |
| 4-ounce loose with- | | | | | | | | | | | | | | | |
| out bag | | 12.0 | 5.2 | 5.0 | 1.7 | 1.3 | .6 | | | | | | | | |

Table 5.--Water-vapor adsorption capacity¹

| Relative humidity : | | Water-vapor adsorption (minimum) | | | | | |
|---------------------|---|----------------------------------|-----------|-----------------|-----------|-----------|---------|
| | | Type II : | Type IV : | Types III and V | | Type III | |
| | | Grade A : | Grade A : | Grade A : | Grade B : | Grade C : | Grade D |
| Percent | : | Percent | : | Percent | : | Percent | : |
| 10 | : | 5.7 | : | 4.3 | : | 5.7 | : |
| | : | | : | | : | 5.7 | : |
| 20 | : | 10.5 | : | 8.6 | : | 10.5 | : |
| | : | | : | | : | 10.0 | : |
| 40 | : | 21.7 | : | 18.2 | : | 21.5 | : |
| | : | | : | | : | 16.0 | : |
| 60 | : | 33.2 | : | 27.7 | : | 28.0 | : |
| | : | | : | | : | 19.0 | : |
| 80 | : | 36.7 | : | 32.9 | : | 31.2 | : |
| | : | | : | | : | 22.0 | : |
| | : | | : | | : | 12.5 | : |
| | : | | : | | : | | : |

¹Table 1 of Interstate Commerce Commission Specification JAN-D-169.

Table 6.--Results of cooling previously heated empty sealed container with rain spray (Test No. 1)

| Time interval : | | Temperature : | | Reduction : | | Spray temperature | |
|-----------------|---|---------------|---|-------------|---|-------------------|---|
| Hours | : | ° F. | : | ° F. | : | ° F. | : |
| 0 | : | 136 | : | ..... | : | 66 | : |
| 1 | : | 78 | : | 58 | : | 61 | : |
| 2 | : | 68 | : | 68 | : | 60 | : |
| 2-3/4 | : | 66 | : | 70 | : | 60 | : |

Table 7.--Time required to heat or cool a metal container holding a hair latex mold from and to constant temperatures.
(Test No. 2)

| Time interval : | Temperature within container : | Increase : | Decrease : | Temperature of heating or cooling medium : |
|---|--------------------------------|------------|------------|--|
| Hours : | ° F. : | ° F. : | ° F. : | ° F. : |
| <u>Heating in hot room</u> | | | | |
| 0 : | 68 : | 0 : | : | 134 : |
| 1/2 : | 107 : | 48 : | : | 134 : |
| 1 : | 126 : | 58 : | : | 134 : |
| <u>Cooling¹ in air at room temperature</u> | | | | |
| 0 : | 134 : | : | 0 : | 67 : |
| 1 : | 88 : | : | 46 : | 72 : |
| 2 : | 76 : | : | 58 : | 72 : |
| <u>Cooling² in water spray</u> | | | | |
| 0 : | 130 : | : | 0 : | 60 : |
| 1/2 : | 80 : | : | 50 : | 60 : |
| 1 : | 62 : | : | 68 : | 60 : |

¹Container left in hot room overnight before cooling was begun.

²Container reheated by placing in hot room overnight before cooling was begun.

Table 8.--Time required to cool a metal container¹ holding hair latex from and to constant temperatures (Test No. 3)

| Time interval : | Temperature : : within container : | Decrease : : | Temperature of : : cooling medium |
|---|---------------------------------------|-----------------|--------------------------------------|
| Hours : | ° F. : | ° F. : | ° F. : |
| <u>Cooling in air at room temperature</u> | | | |
| 0 : | 136 : | 0 : | 70 : |
| 1 : | 90 : | 46 : | 70 : |
| 2 : | 82 : | 54 : | 70 : |
| 3 : | 78 : | 58 : | 70 : |
| <u>Cooling in water spray</u> | | | |
| 0 : | 136 : | 0 : | 66 : |
| 1 : | 78 : | 58 : | 60 : |
| 2 : | 68 : | 68 : | 60 : |

¹—Same container used throughout test.

Table 9.—Time required to heat and cool to constant temperatures a package¹ consisting of a generator, dunnage, cushioning material, and silica gel in a metal container (Test No. 4)

| Time interval | Temperature within container | Increase | Decrease | Temperature of heating medium |
|--|------------------------------|----------|----------|-------------------------------|
| Hours | ° F. | ° F. | ° F. | ° F. |
| <u>Heating in a hot room</u> | | | | |
| 0 | 70 | 0 | ..... | 130 |
| 1/2 | 108 | 38 | ..... | 130 |
| 1 | 116 | 46 | ..... | 130 |
| 1-1/2 | 118 | 48 | ..... | 130 |
| 2 | 120 | 50 | ..... | 130 |
| <u>Cooling from 120° F. in air at room temperature</u> | | | | |
| 0 | 120 | ..... | 0 | 74 |
| 1/2 | 96 | ..... | 24 | 74 |
| 1 | 92 | ..... | 28 | 74 |
| <u>Cooling from 140° F. in air at room temperature</u> | | | | |
| 0 | 140 | ..... | 0 | 70 |
| 1 | 106 | ..... | 34 | 70 |
| 2 | 96 | ..... | 44 | 70 |
| 2-1/2 | 94 | ..... | 46 | 70 |
| <u>Cooling from 140° F. in water spray</u> | | | | |
| 0 | 140 | ..... | 0 | 64 |
| 1 | 96 | ..... | 44 | 64 |
| 2 | 86 | ..... | 54 | 64 |
| 3 | 80 | ..... | 60 | 64 |
| 4 | 76 | ..... | 64 | 64 |
| 5 | 74 | ..... | 66 | 64 |

¹Same package used throughout this test.

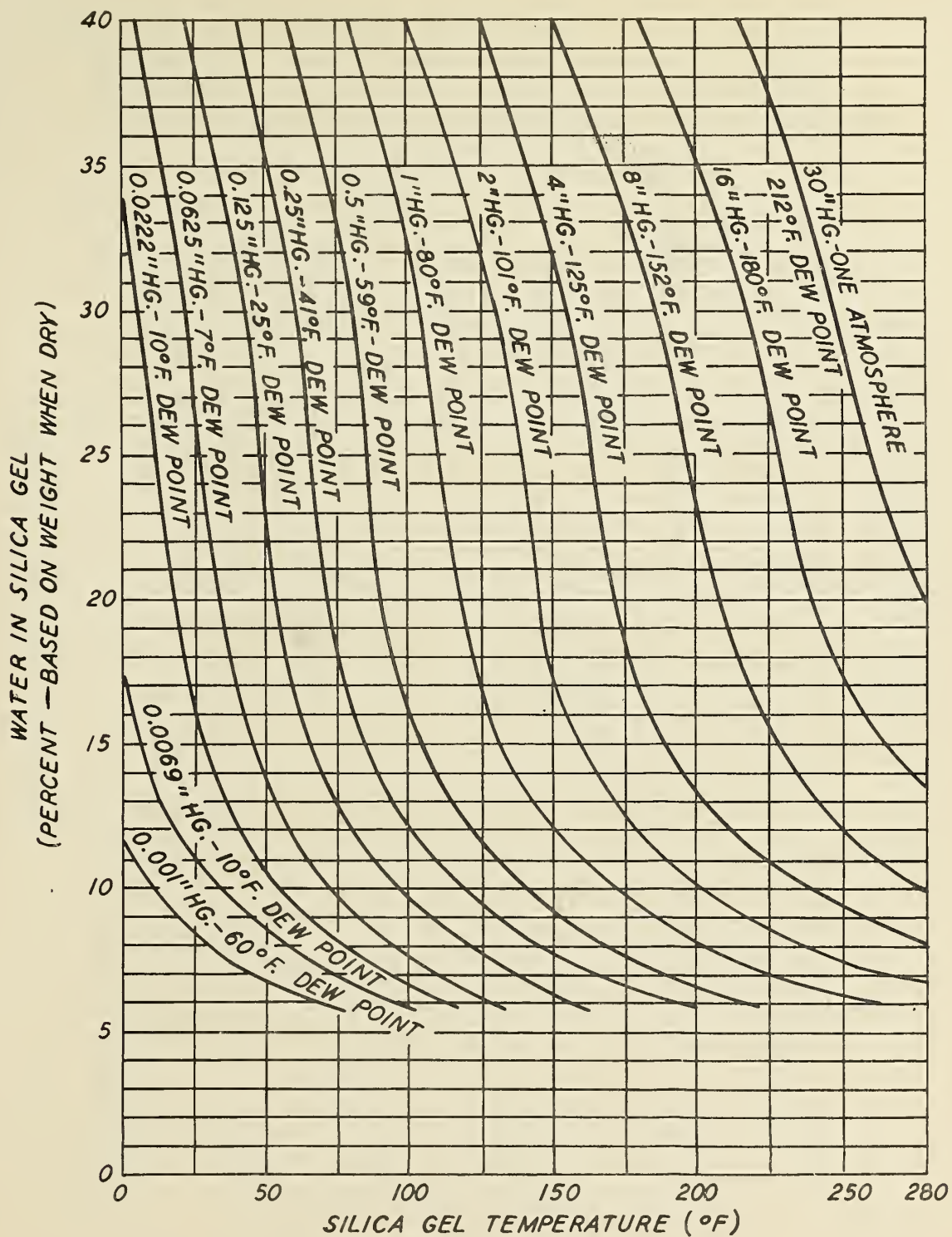


Figure 1.--Silica gel - water vapor equilibrium isopiestic for 0.70 density silica gel. (This graph from a paper entitled "Silica Gel" by F. C. Dehler of the Davison Chemical Corporation, presented at George Washington University, Washington, D. C., June 23, 1941.)

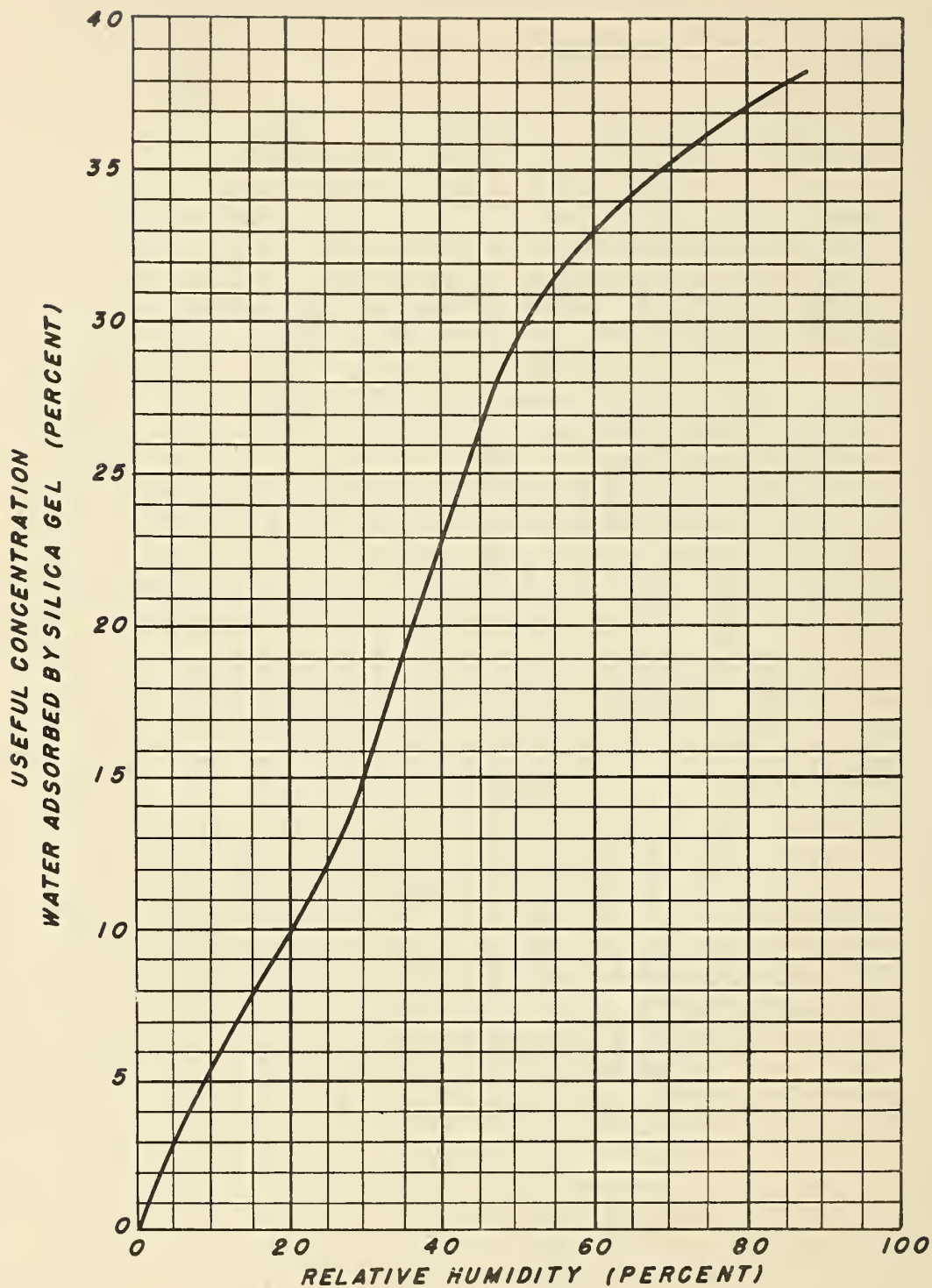


Figure 2.--Relation of equilibrium useful concentration to relative humidity. (This graph from a paper entitled "Silica Gel" by F. C. Dehler of the Davison Chemical Corporation, presented at George Washington University, Washington, D. C., June 23, 1941.)

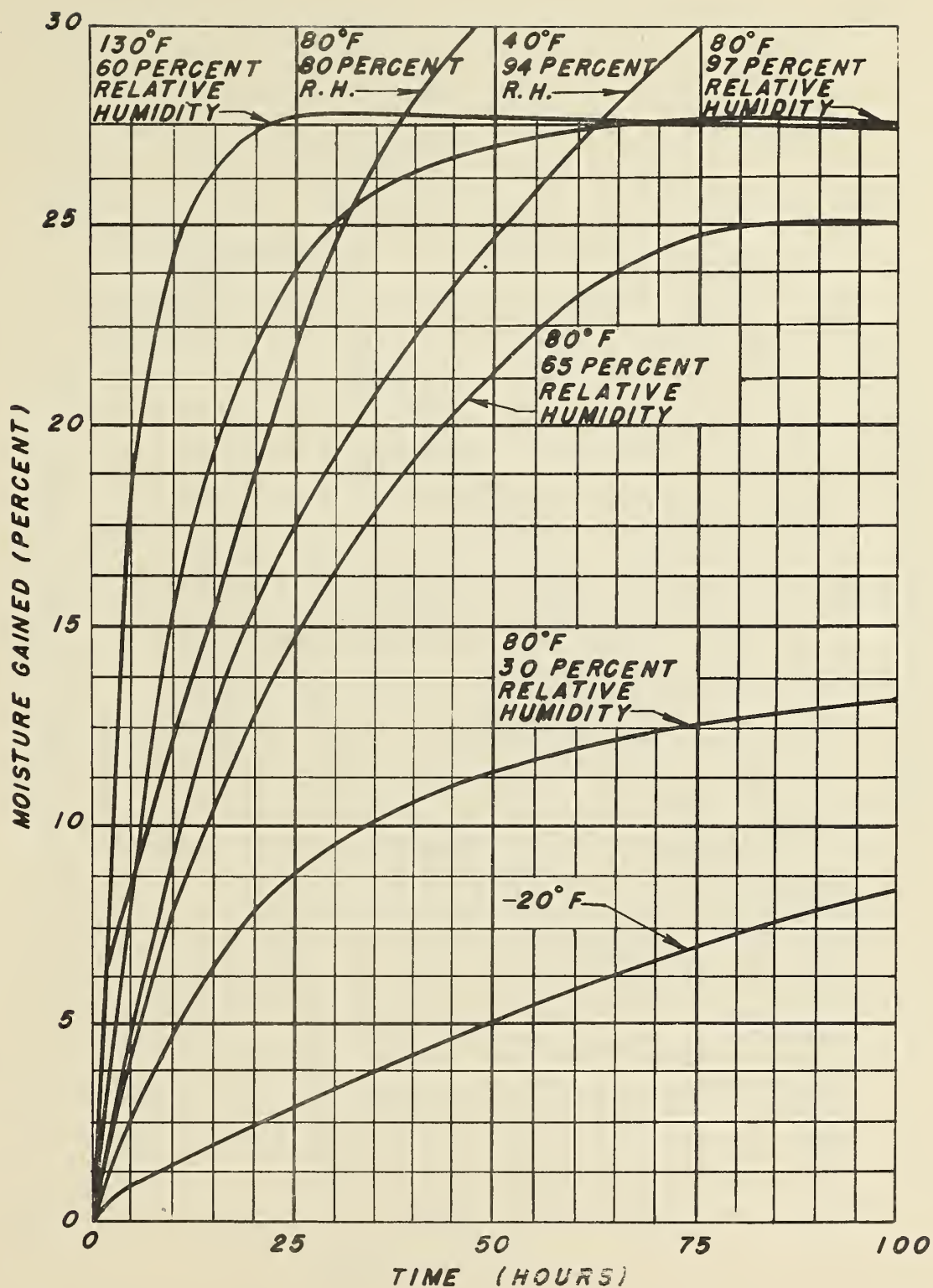


Figure 3.--Percentage of moisture gained by 1-ounce bags of silica gel exposed in open-top No. 2 metal cans to various relative humidity and temperature conditions.

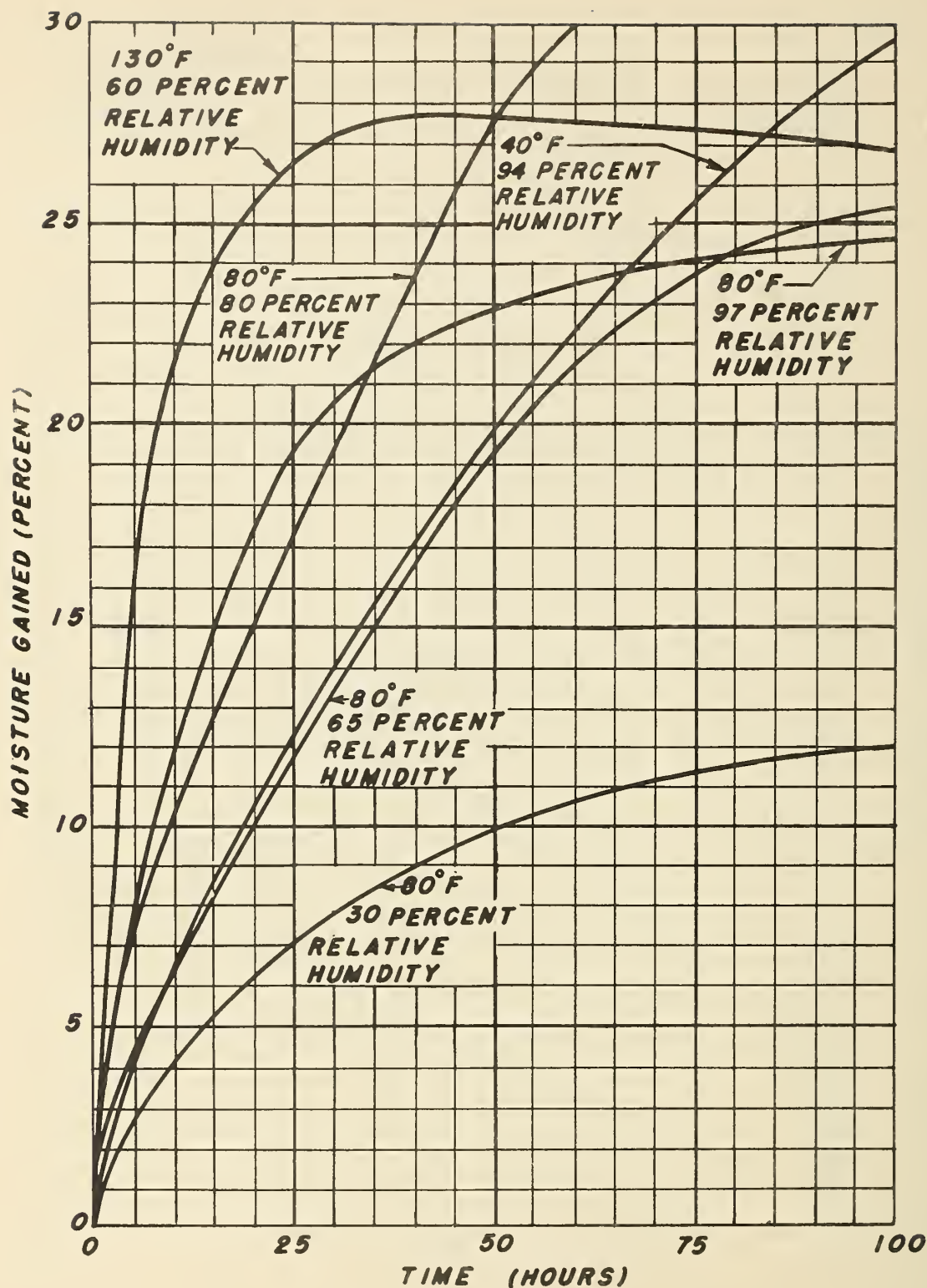


Figure 4.--Percentage of moisture gained by 2-ounce bags of silica gel exposed in open-top No. 2 metal cans to various relative humidity and temperature conditions.

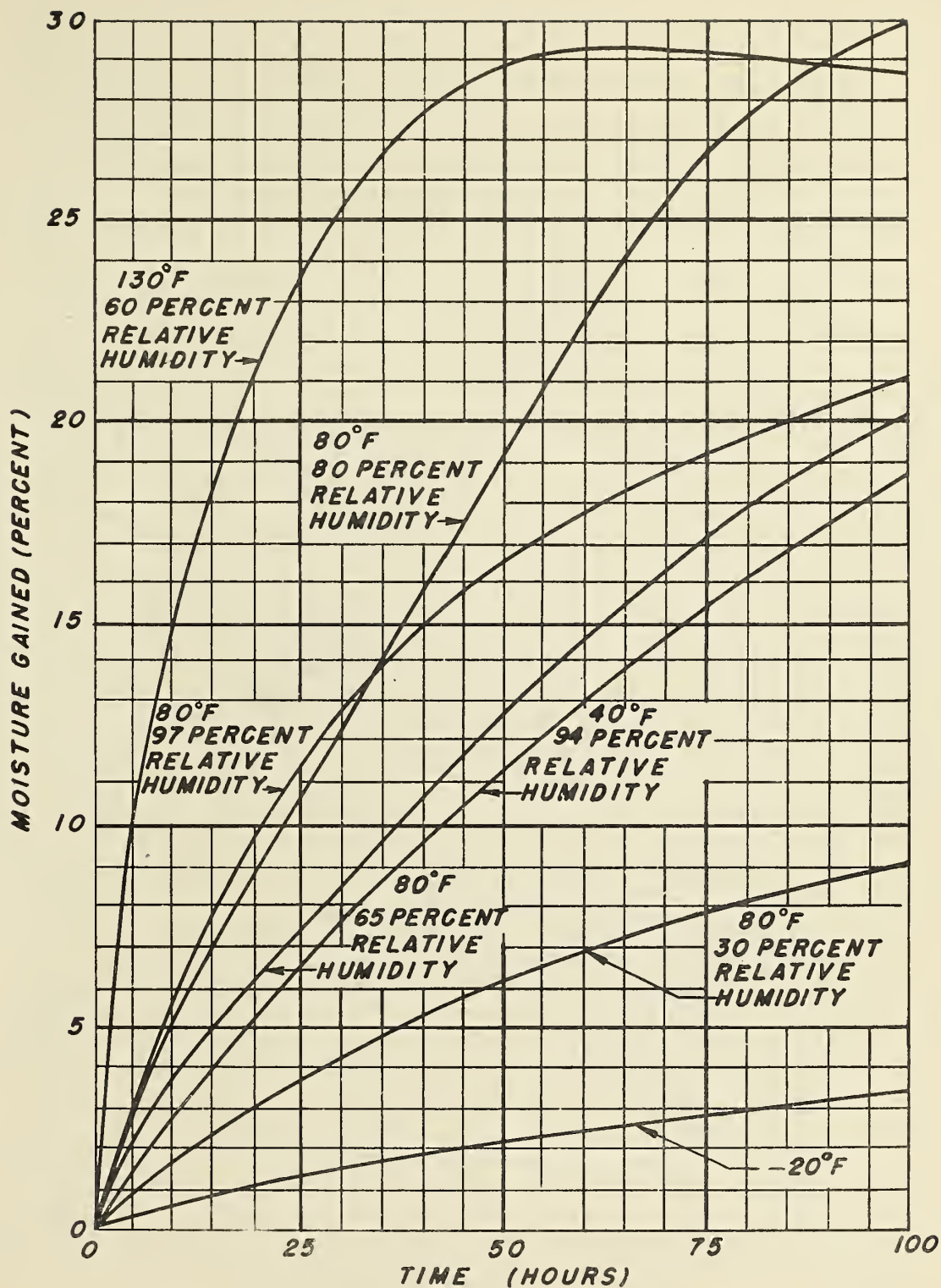


Figure 5.--Percentage of moisture gained by 4-ounce bags of silica gel exposed in open-top No. 2 metal cans to various relative humidity and temperature conditions.

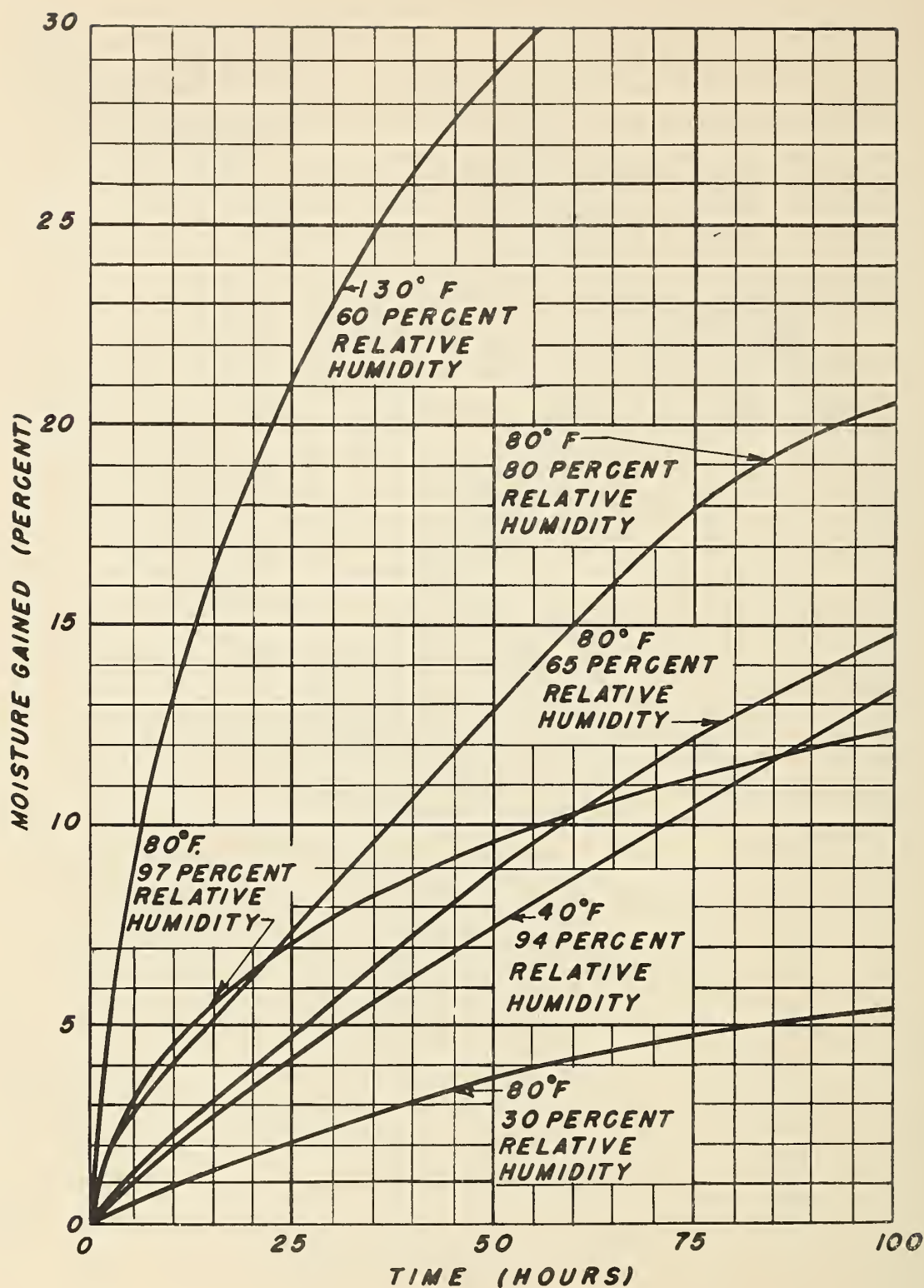


Figure 6.--Percentage of moisture gained by 8-ounce bags of silica gel exposed in open-top No. 2 metal cans to various relative humidity and temperature conditions.

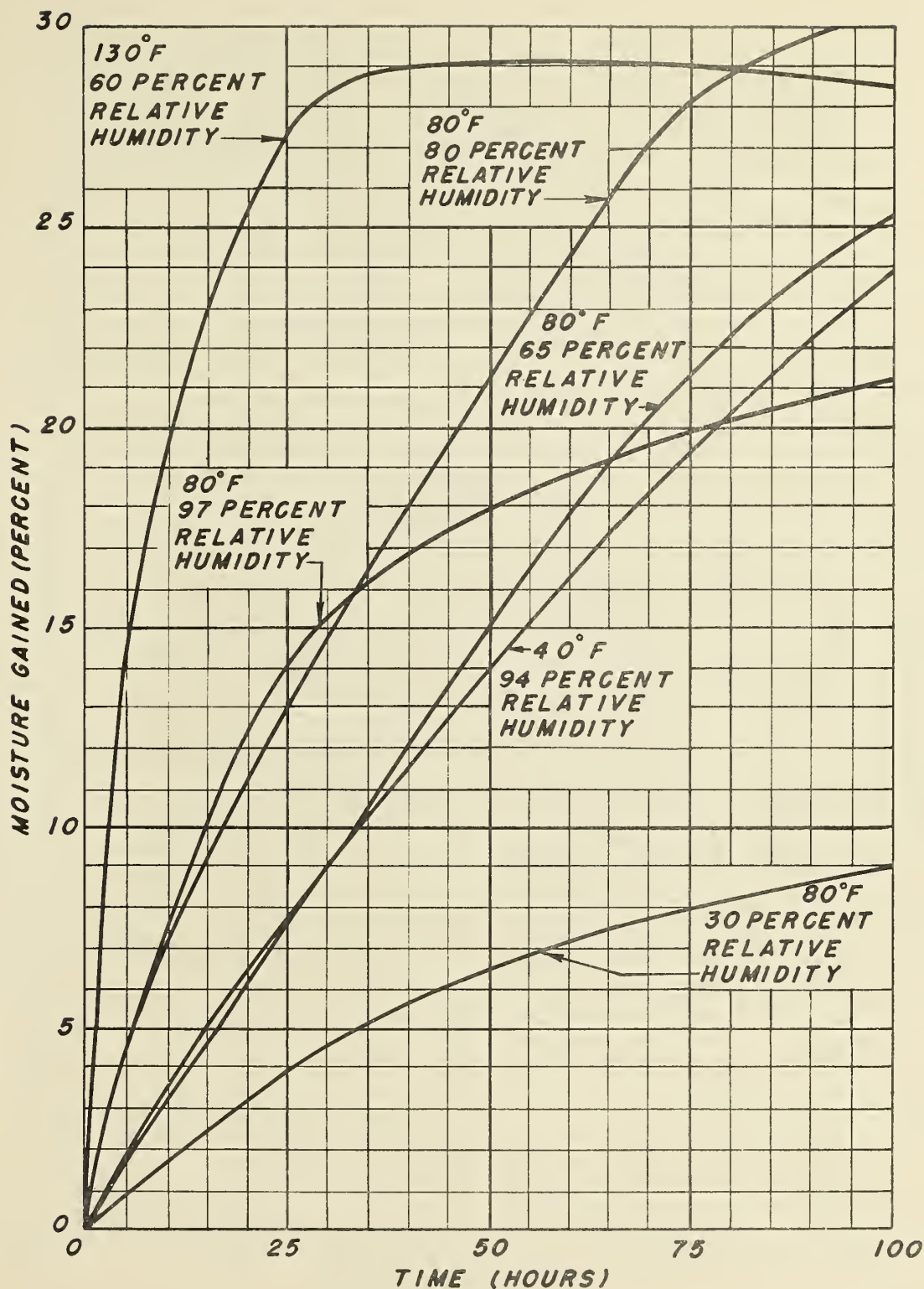


Figure 7.--Percentage of moisture gained by 4 ounces of loose silica gel exposed in open-top No. 2 metal cans to various relative humidity and temperature conditions.

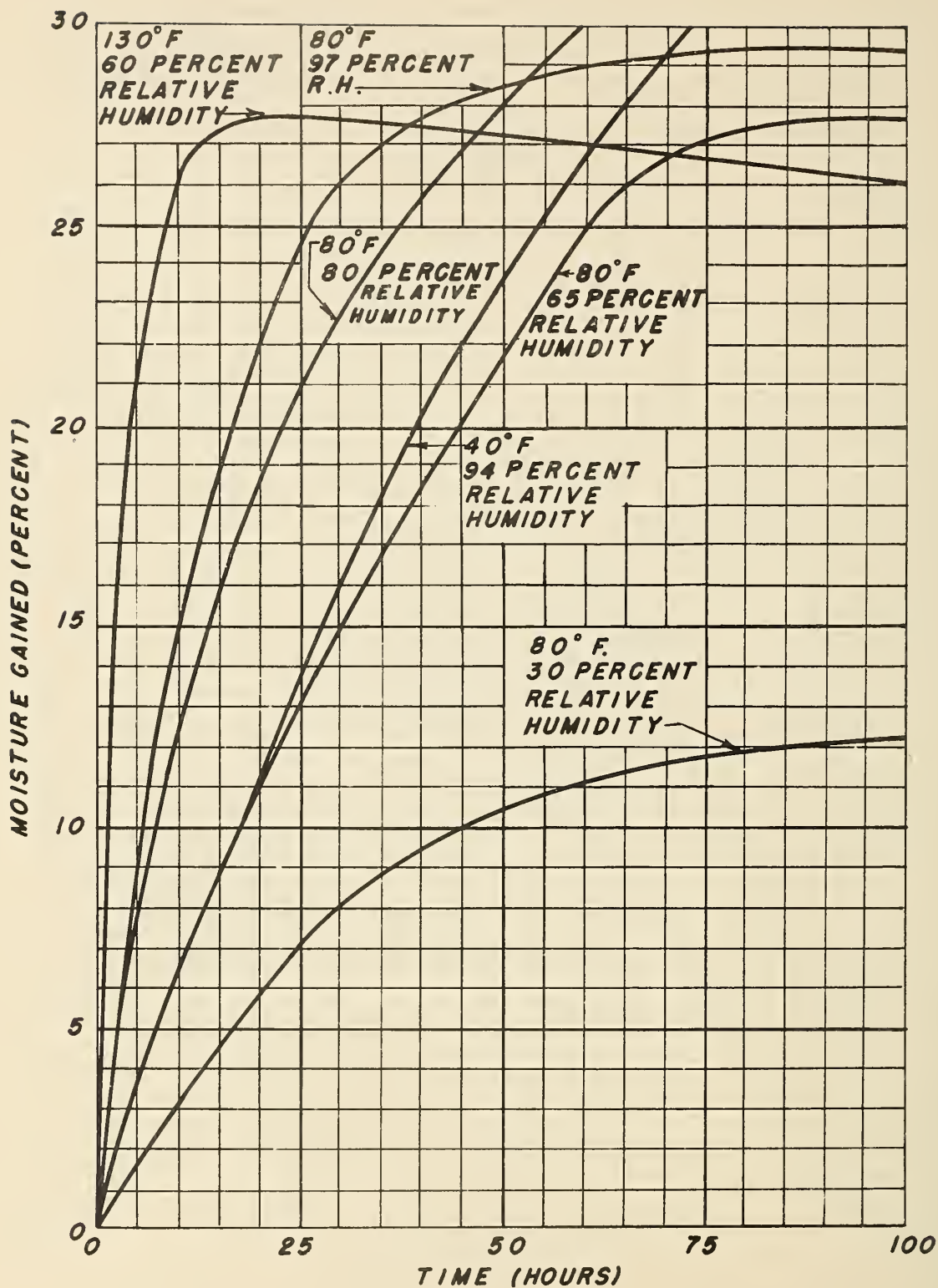


Figure 8.--Percentage of moisture gained by 2 ounces of loose silica gel exposed in open-top No. 2 metal cans to various relative humidity and temperature conditions.

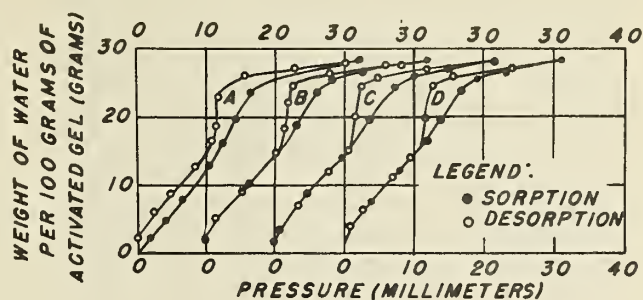


Figure 9.--Hysteresis loop in the sorption of water on silica gel. A, first; B, second; C, third; D, nineteenth. (This figure taken from a report by B. S. Rao, "Hysteresis in Sorption," Journal Physical Chemistry, Page 513, Vol. 45, 1941.)

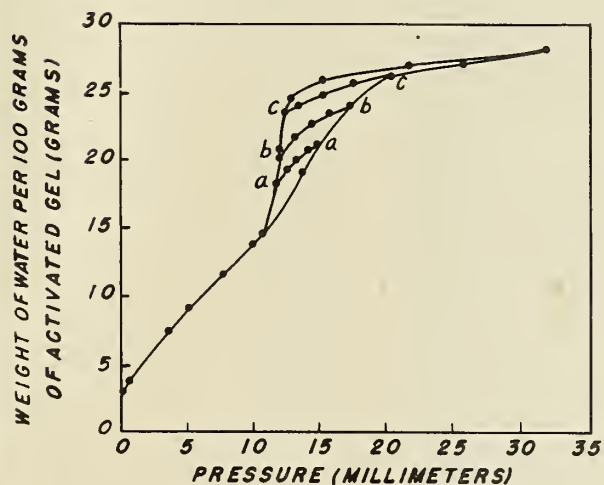


Figure 10.--Scanning of the hysteresis loop (sorption to desorption) in the sorption of water on silica gel. (This figure taken from a report by B. S. Rao, "Hysteresis in Sorption," Journal Physical Chemistry, Page 513, Vol. 45, 1941.)

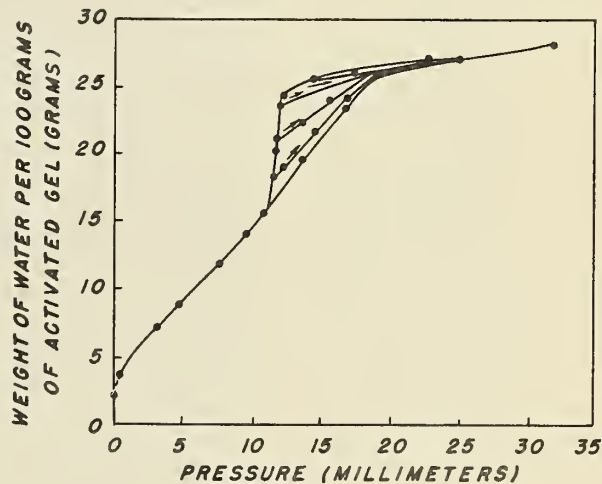


Figure 11.--Scanning of the hysteresis loop (desorption to sorption) in the sorption of water on silica gel. (This figure taken from a report by B. S. Rao, "Hysteresis in Sorption," Journal Physical Chemistry, page 513, vol. 45, 1941.)

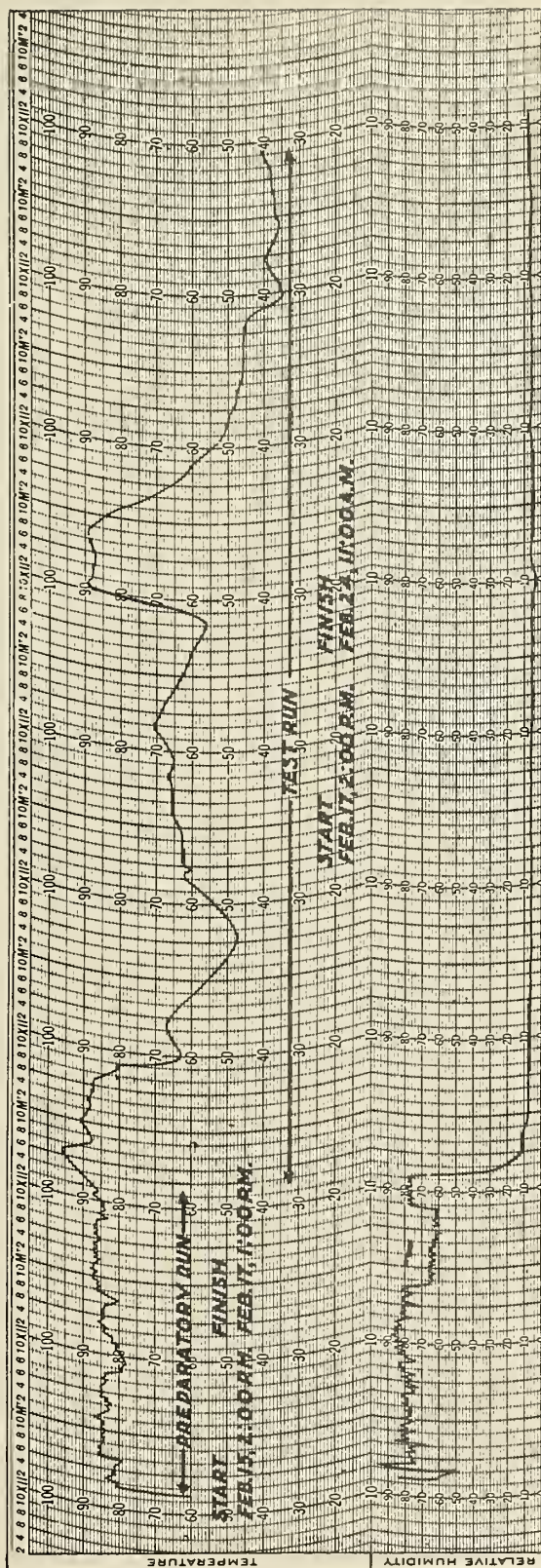


Figure 13.--The exact conditions obtained within a container which includes a predetermined amount of desiccant. After seasoning for several days to allow all surfaces and material to reach equilibrium with warm air of reasonably high relative humidity desiccant was inserted and the container closed. (This graph taken from a report published by the Davison Chemical Corporation, Baltimore, Md.)

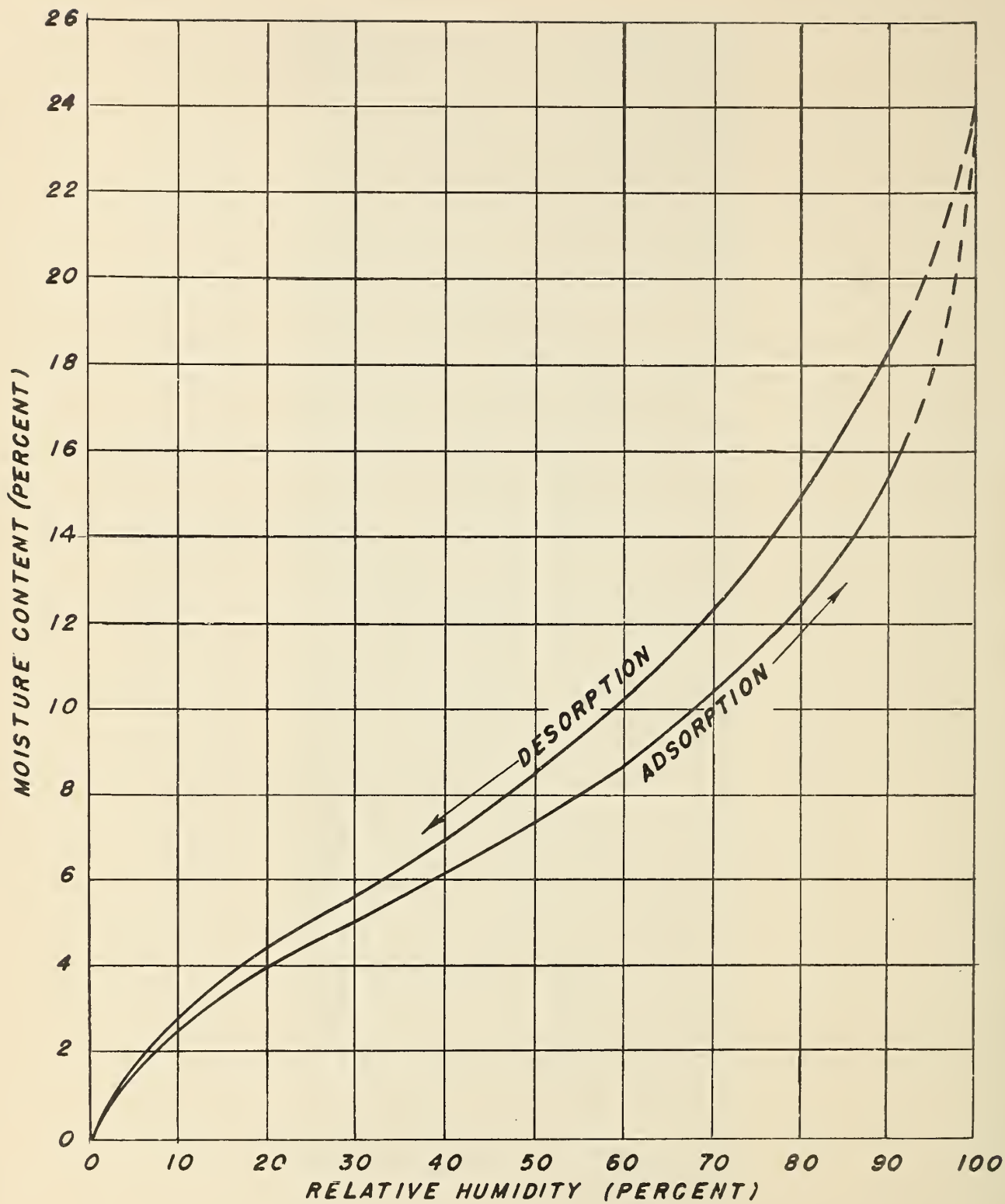


Figure 14.--Desorption isotherms from above fiber saturation of unbleached, unbeaten Western hemlock sulphite pulp.

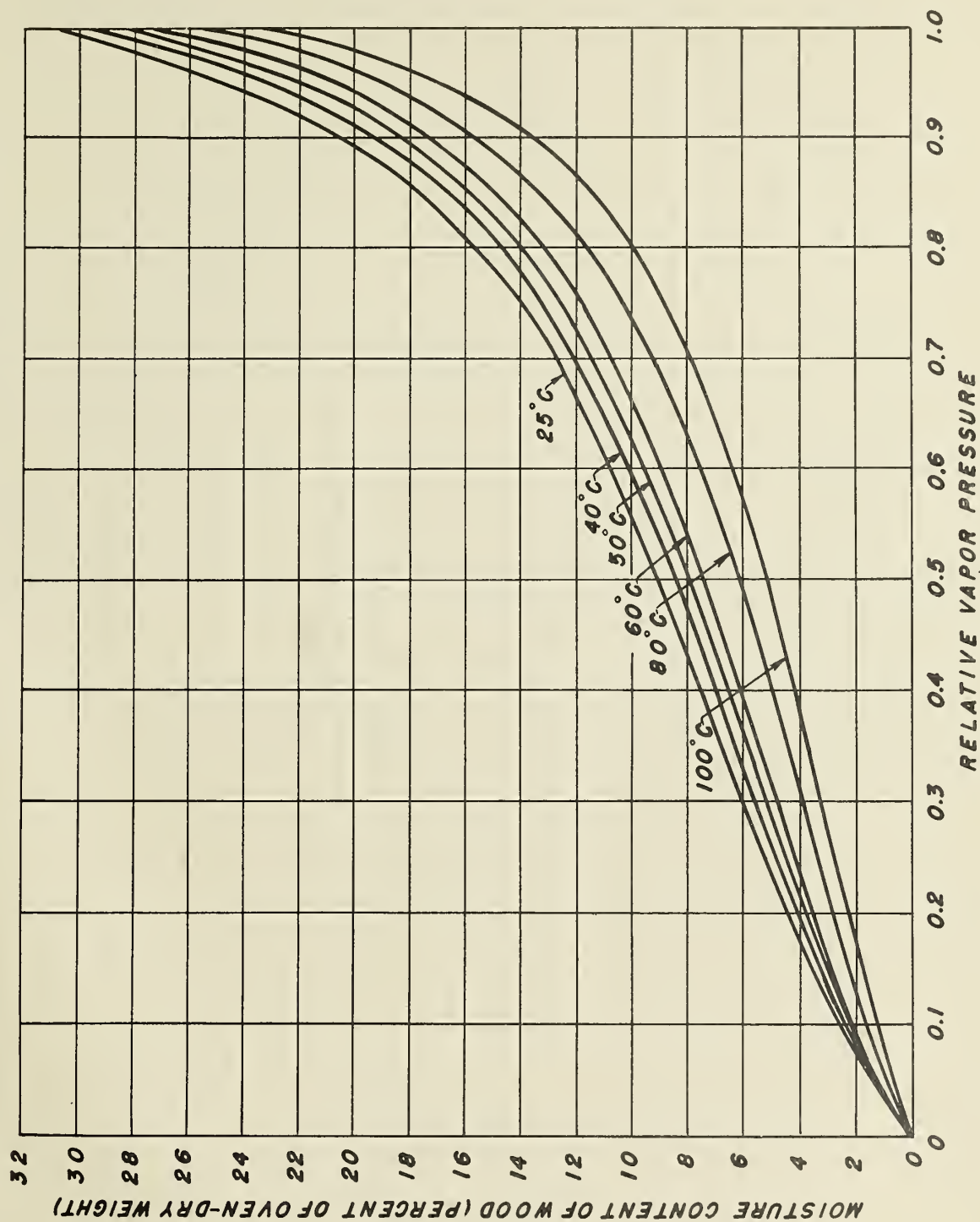


Figure 15.--Relation of the equilibrium moisture content of wood to the relative humidity of the surrounding atmosphere at various temperatures.

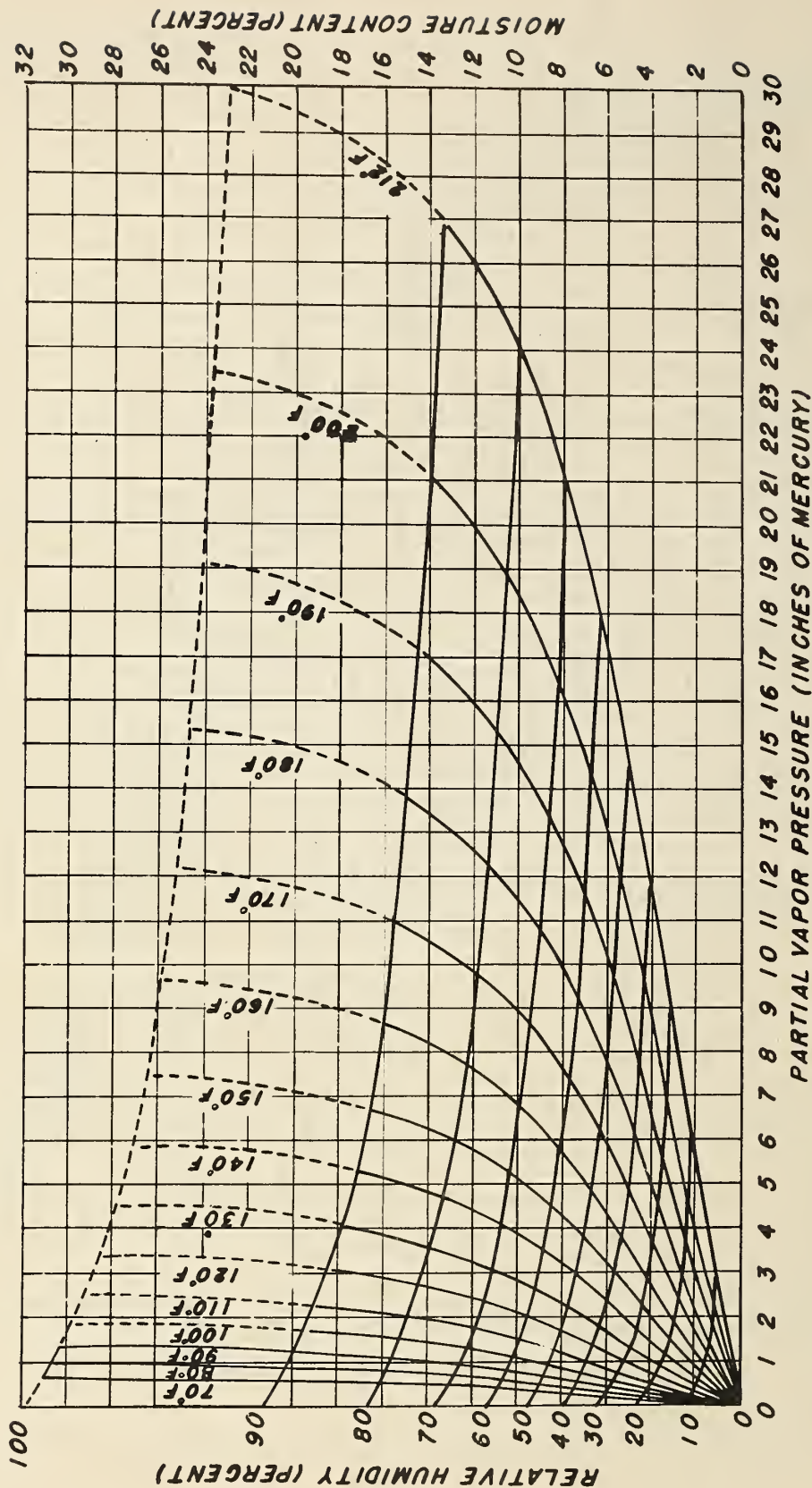


Figure 16.---Moisture content of Sitka spruce at equilibrium with the indicated temperature, partial vapor pressure, and relative humidity.